UNIVERSITÀ DELLA CALABRIA
Facoltà di SCIENZE MATEMATICHE, FISICHE E NATURALI

ATLAS EXPERIMENT

INFN Istituto Nazionale di Fisica Nucleare

Search for displaced Lepton Jets in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS Experiment…

28th IMPRS Workshop

March 17th 2014
-Munich, GERMANY-

Valentina Cairo

University of Calabria, INFN
-Cosenza, ITALY-

…and other (hardware) works!

Outline

- **Analysis: Introduction**
  - **Standard Model and Beyond**
  - **Beyond the Standard Model: Hidden Sectors**
  - **Higgs Boson Decays in the Hidden Sector**
  - **ATLAS Experiment at the Large Hadron Collider**

- **Analysis: Search for Displaced Lepton Jets**
  - **Definitions and types**
  - **Triggers**
  - **Lepton Jet Gun Monte Carlo**
  - **Cuts**

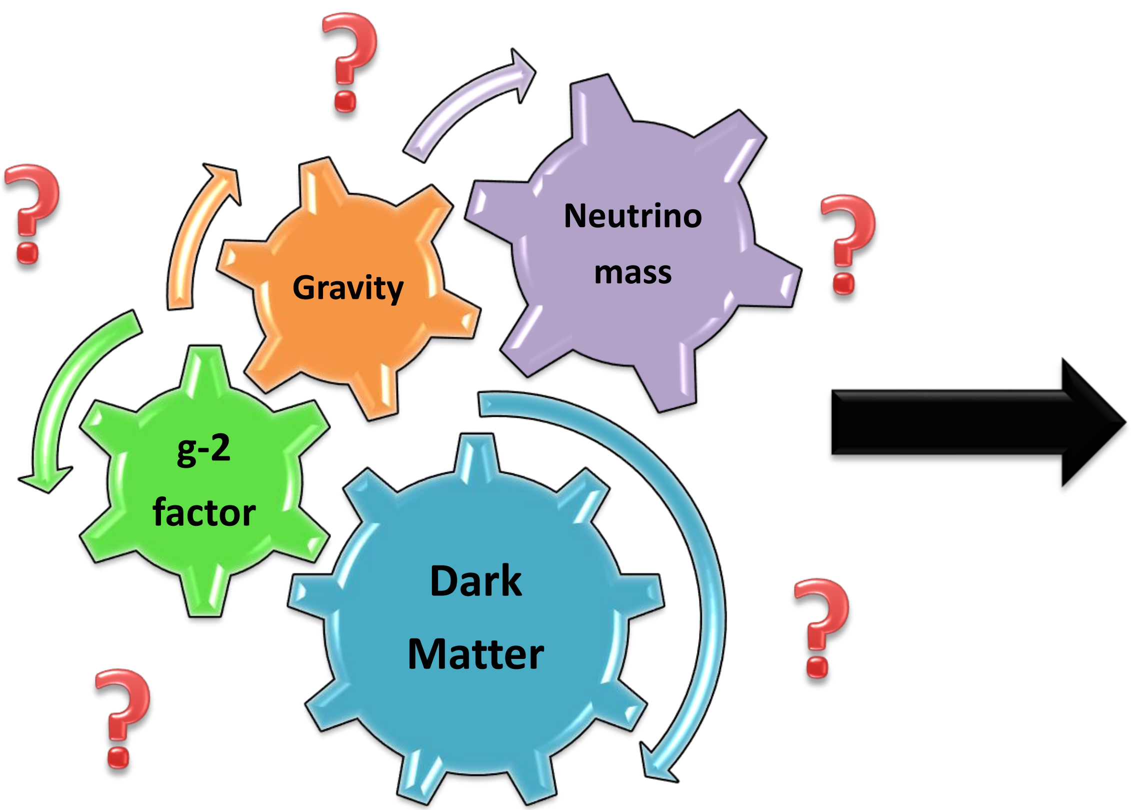
- **Analysis: Background Events**
  - **Cosmics**
  - **QCD**

- **Analysis: Hidden Valley Models**

- **Analysis: Systematics**

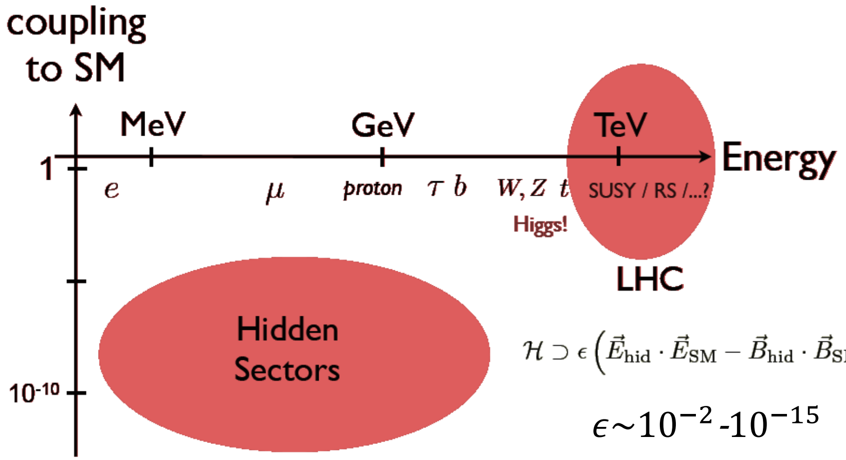
- **Hardware: Micro-Pattern Gas Detectors**

Standard Model and Beyond



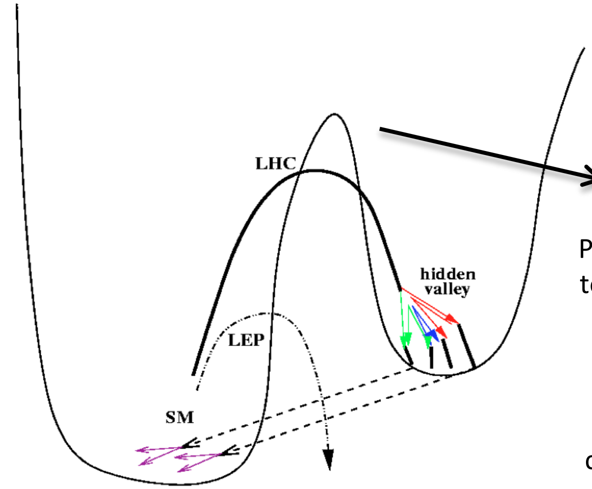
Physics Beyond the Standard Model

Beyond the Standard Model: Hidden Sector



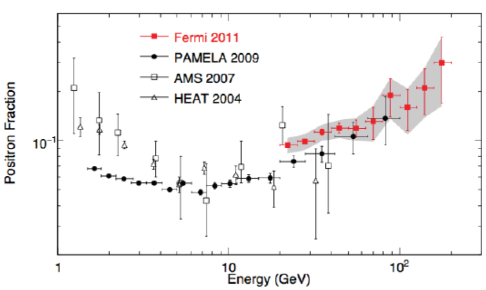
$$\mathcal{H} \supset \epsilon \left(\vec{E}_{\rm hid} \cdot \vec{E}_{\rm SM} - \vec{B}_{\rm hid} \cdot \vec{B}_{\rm SM} \right)$$

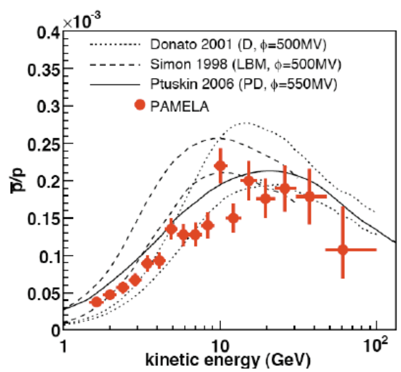
$$\epsilon \sim 10^{-2}\text{-}10^{-15}$$



Potential barrier to overcome for the axcess to the hidden sector. LHC energy could allow the observation.

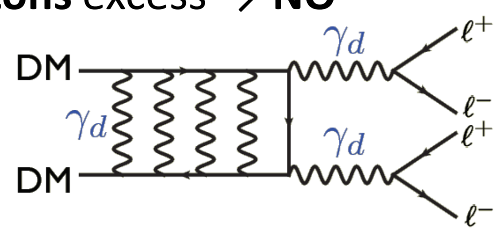
Cosmics excess





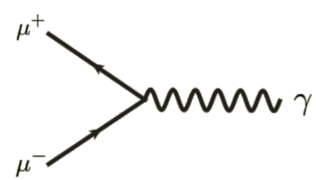
Positrons excess → **YES**

Antiprotons excess → **NO**

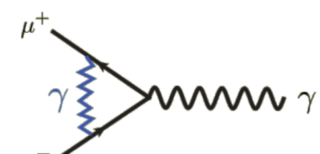


$(g_s-2)_\mu$ *anomaly*

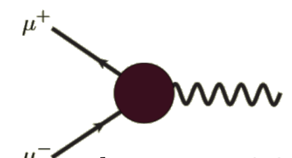
$$\vec{\mu} = g_s \left(\frac{q}{2m} \right) \vec{s}$$



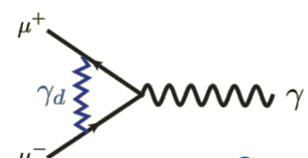
$g_s = 2$



$g_s \neq 2$



$th - exp = 3.2\sigma$

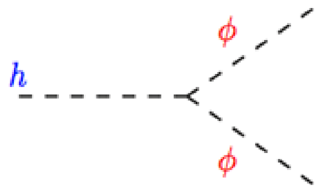


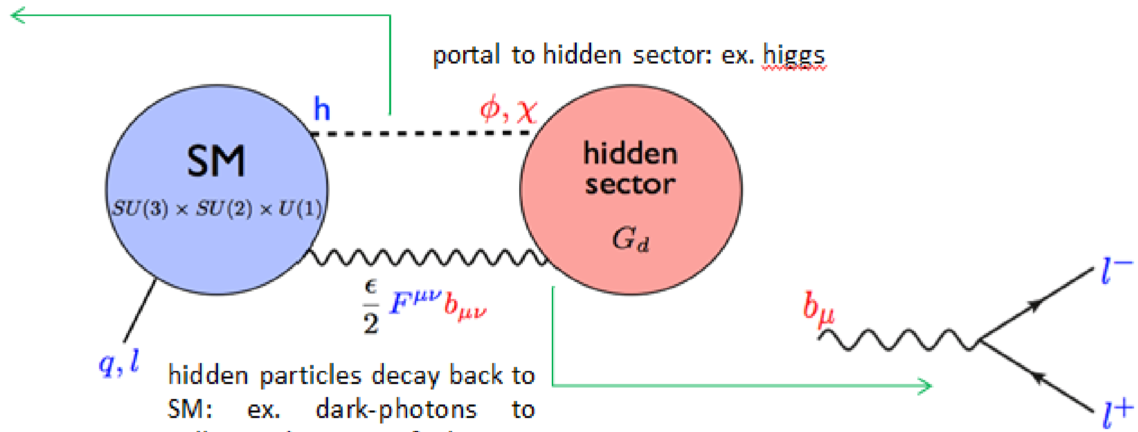
$g_s = 2$

Higgs Boson Decays in the Hidden Sector

STANDARD MODEL → July 4th 2012 : ATLAS and CMS discover an HiggsBoson-like particle

BEYOND the STANDARD MODEL → Higgs Boson rare decays in the Hidden Sector.





hidden particles decay back to SM: ex. dark-photons to collimated pair of leptons (Lepton Jets)

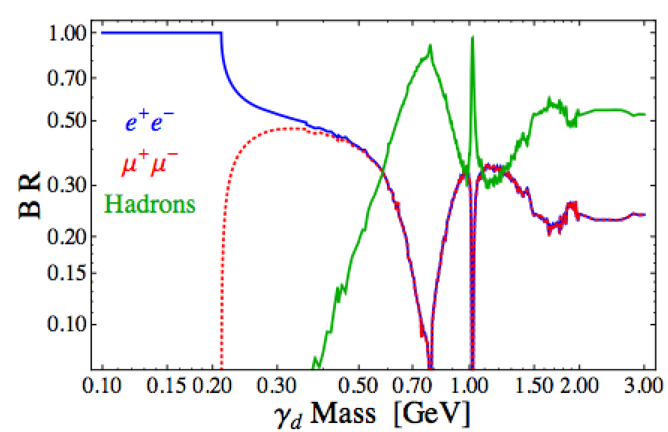
$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} b_{\mu\nu} + m^2_{\gamma_d} b^2$$

$$H\ (SM) \rightarrow instable\ particles\ (hs)$$

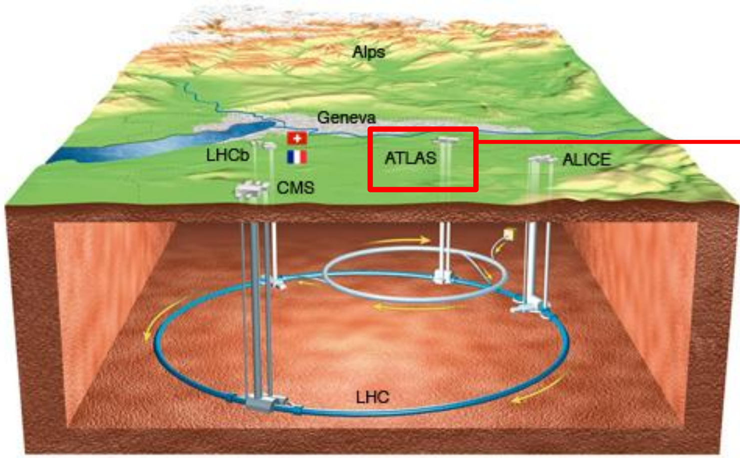
$$instable\ part\ (hs) \rightarrow long\ lived\ light\ particles\ (\gamma_d)$$

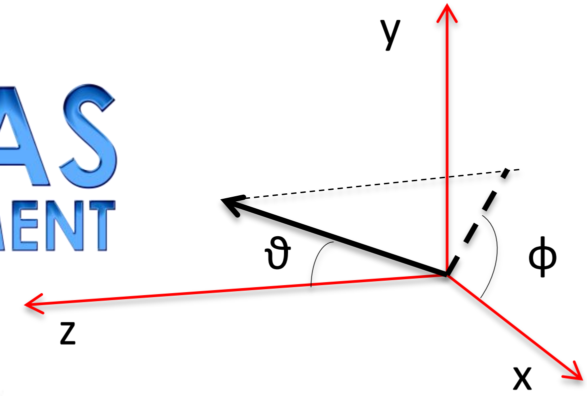
$$\gamma_d\ (hs) \rightarrow e, \mu, \pi\ pairs\ - Lepton\ Jet - (SM)$$

γ_d Branching Ratio

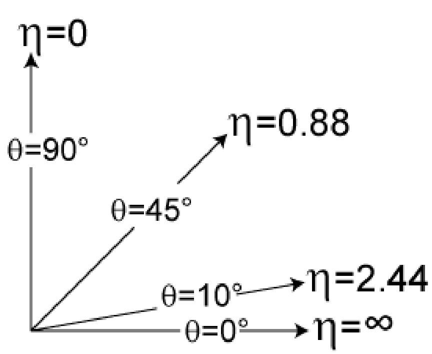


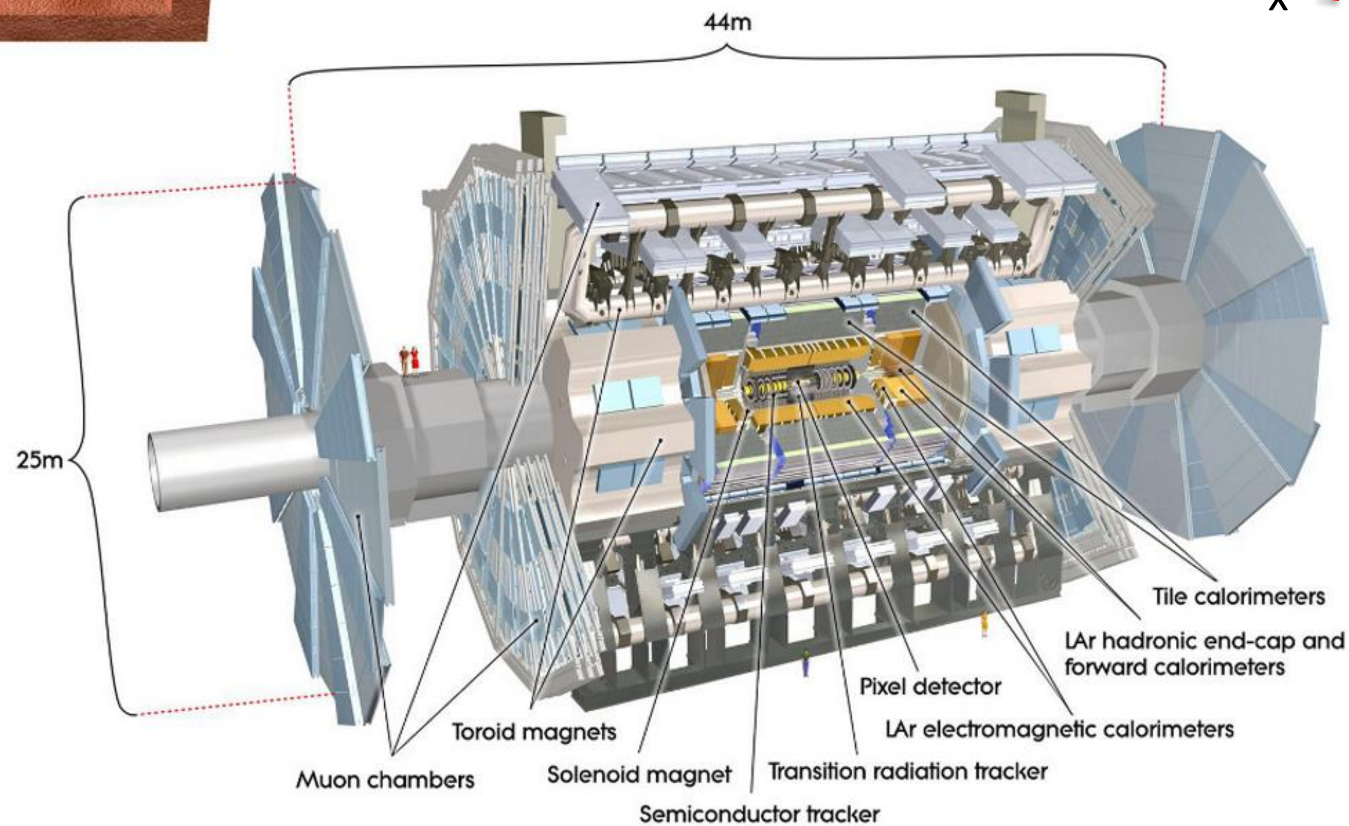
ATLAS Experiment at the Large Hadron Collider





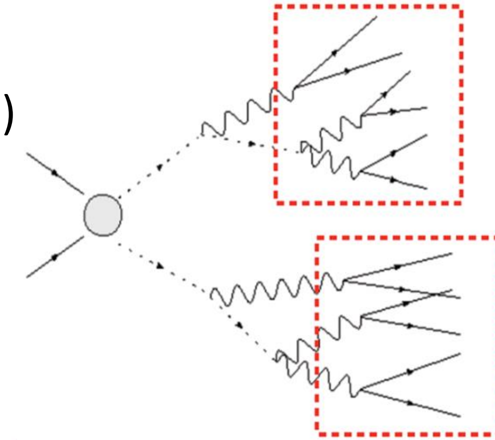
$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$





Search for Lepton Jets: Definitions and Types

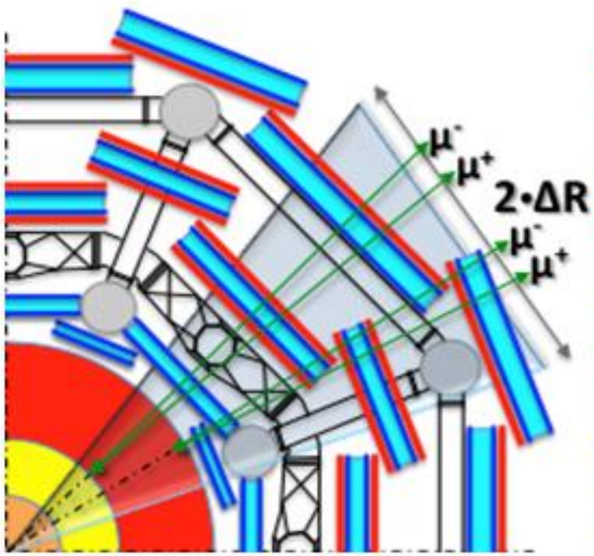
- Model Indipendent Search
- “Displaced” (o “non-prompt”) = collimated jet of light particles originated further the last Pixel plane in the Inner Detector (>15cm)

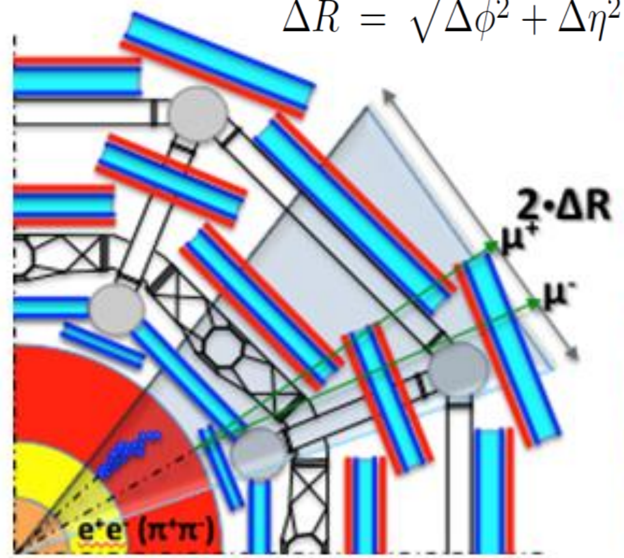


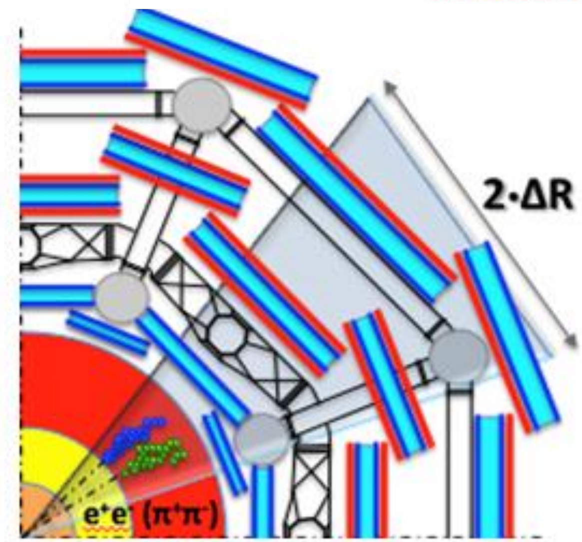
A Lepton Jet is defined starting from two different objects:

- tracks inside the muon spectrometer;
- jets into the calorimeter.

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$







Type 0:
≥2 MS tracks clustered in ΔR and no jets in the cone

Only MUONS

Type 1:
≥2 MS tracks and one jet clustered in ΔR

MUONS e PIONS/ELECTRONS

Type 2:
Only one jet with low em fraction and narrow width

PIONS/ELECTRONS in hadr cal

Triggers

Triggers for non-prompt Lepton Jets:

✓ **Muonic Trigger (EF_3mu6_MSonly)**

requires ≥ 3 muons with pT > 6 GeV only in Muon Spectrometer (MS)

This trigger selects displaced Lepton Jets with high muonic content

✓ **Calorimetric Trigger (EF_j35_a4tcem_L1TAU_LOF_HV)**

requires log(h/e) > 1.2 for the jet

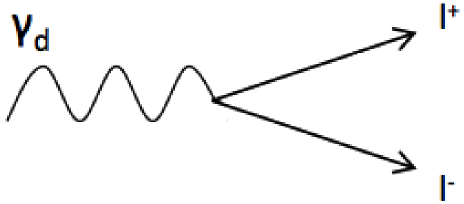
This trigger selects displaced Lepton Jets with high electronic/pionic content in the HCAL

Lepton Jet Gun Monte Carlo

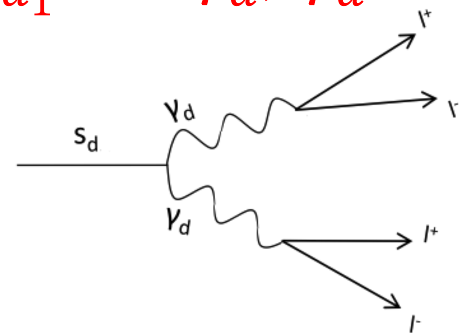
- Lepton Jet Gun Monte Carlo to study cuts and detector acceptance

Samples

$\gamma_d \rightarrow l^+ l^-$



$s_{d_1} \rightarrow 2\,\gamma_d;\ \gamma_d \rightarrow l^+ l^-$



Dark photon parameters:

- $m = 50, 150, 400, 900, 1500$ MeV;
- p_T uniform in the range $[5, 100]$ GeV;
- η uniform in the range $[-2.5, 2.5]$;
- ϕ uniform in the range $[-3.14, 3.14]$ rad;
- Transverse and longitudinal polarization;
- BR in e, μ, π related to the dark photon mass.

100 k events for each sample.

Scalar parameters :

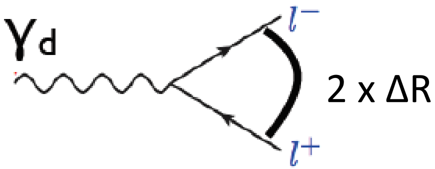
- $m = 1, 2, 5, 10$ GeV;
- p_T uniform in $[5, 100]$, $[10, 100]$, $[15, 100]$ GeV ;
- η uniform in the range $[-2.5, 2.5]$;
- ϕ uniform in the range $[-3.14, 3.14]$ rad.

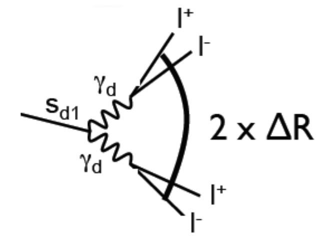
Dark photon parameters:

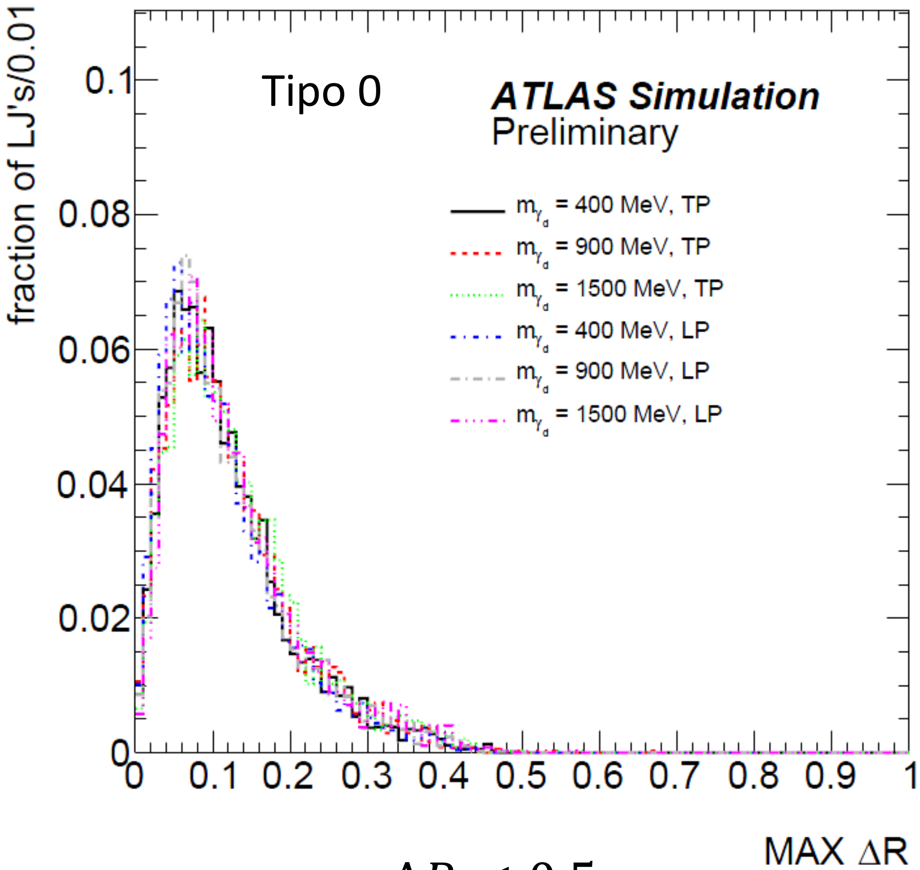
- $m = 50, 150, 400, 900, 1500$ MeV;
- No polarization;
- BR in e, μ, π related to the dark photon mass.

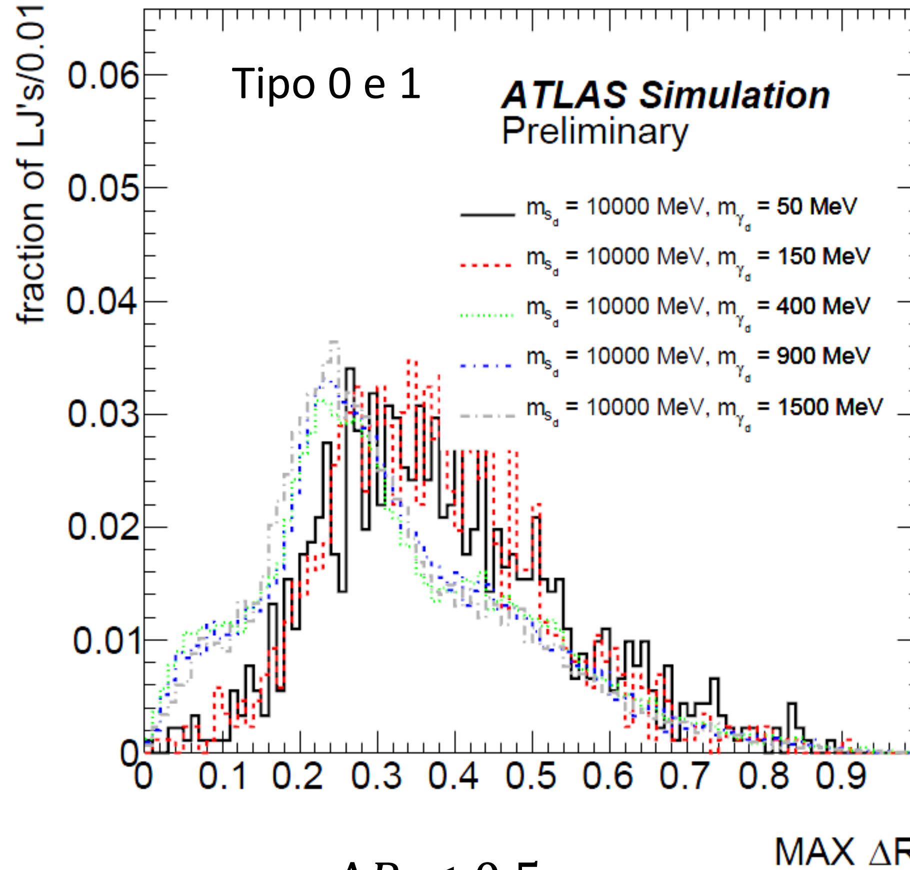
100 k events for each sample.

Lepton Jets Angular Aperture ΔR









$\Delta R < 0.5$

$complete\ efficiency$

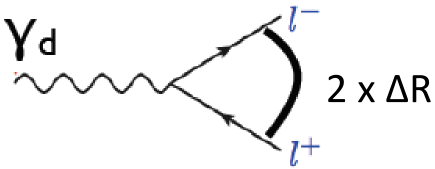
NO difference in the two polarization states

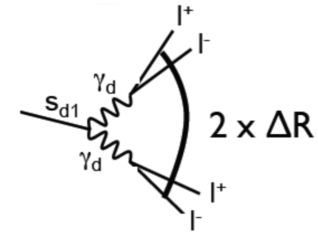
$\Delta R < 0.5$

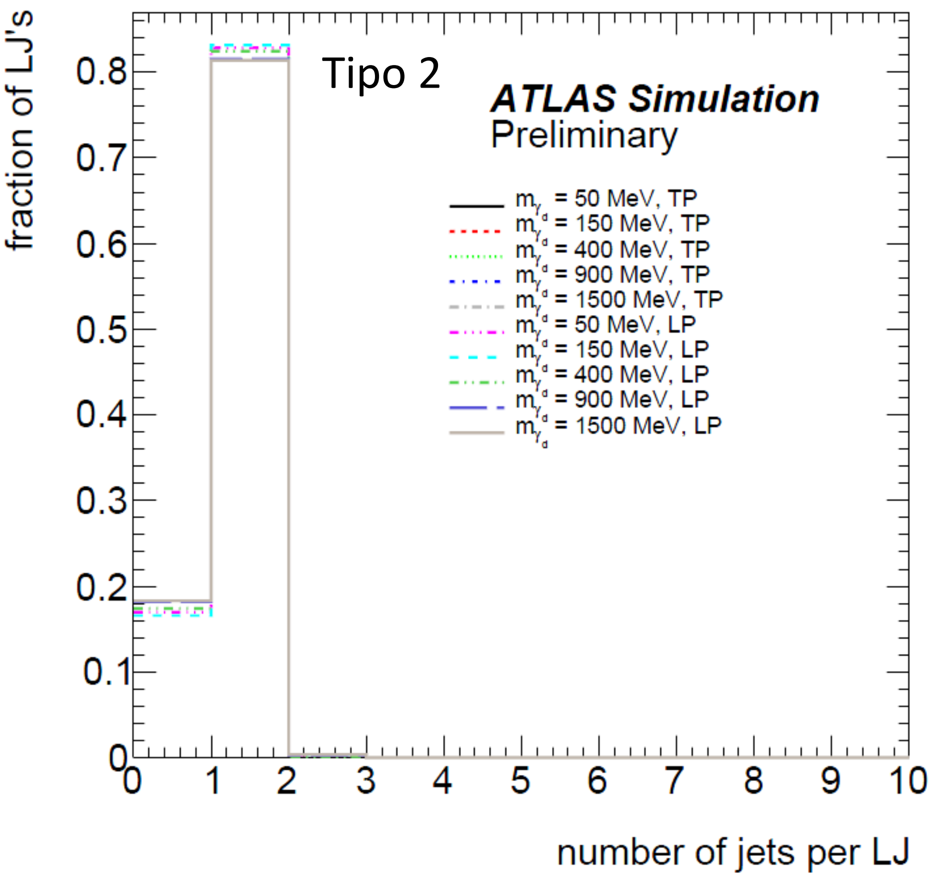
$efficiency > 82\%$

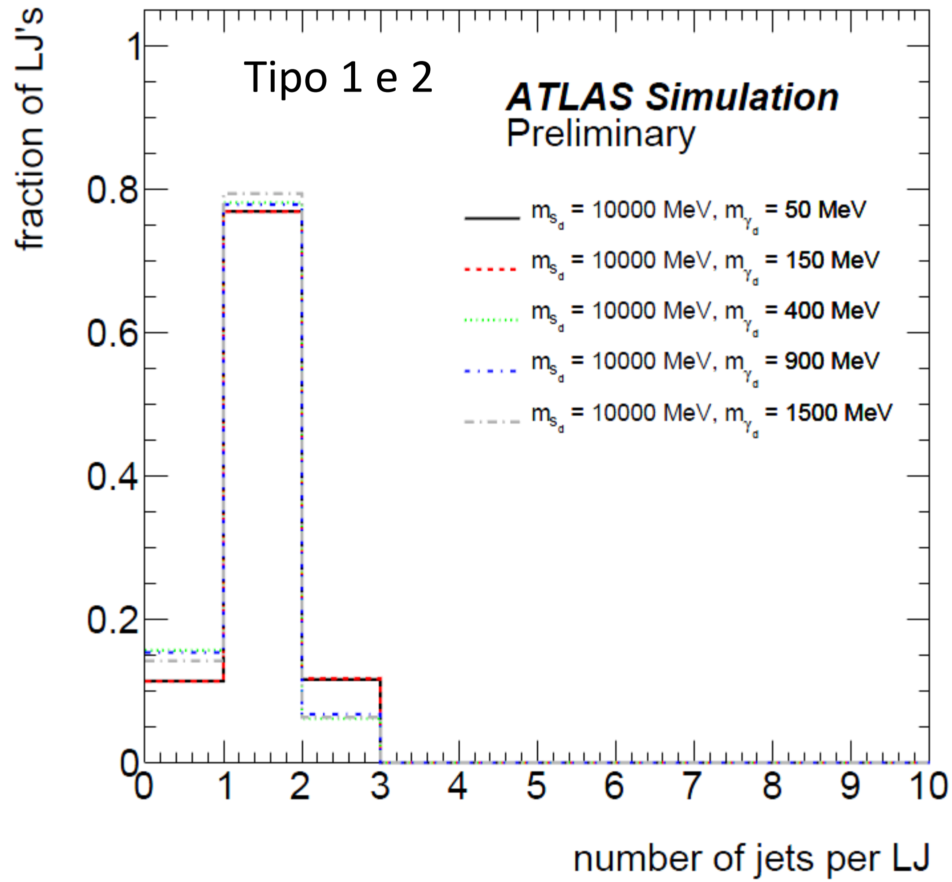
NO difference in the two polarization states

Number of jets per Lepton Jet





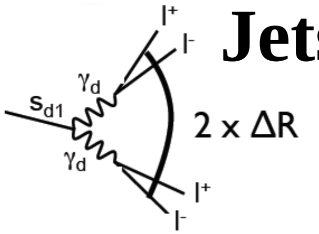




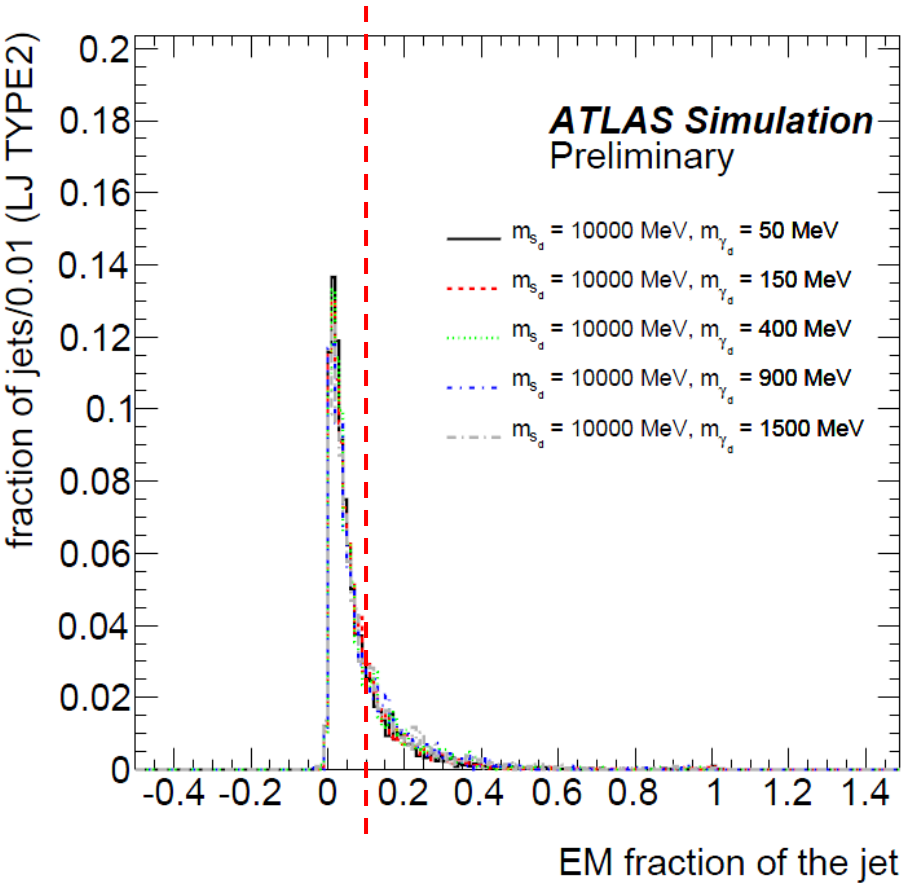
Single jet reconstruction efficiency $\sim 80\%$
NO difference in the two polarization states

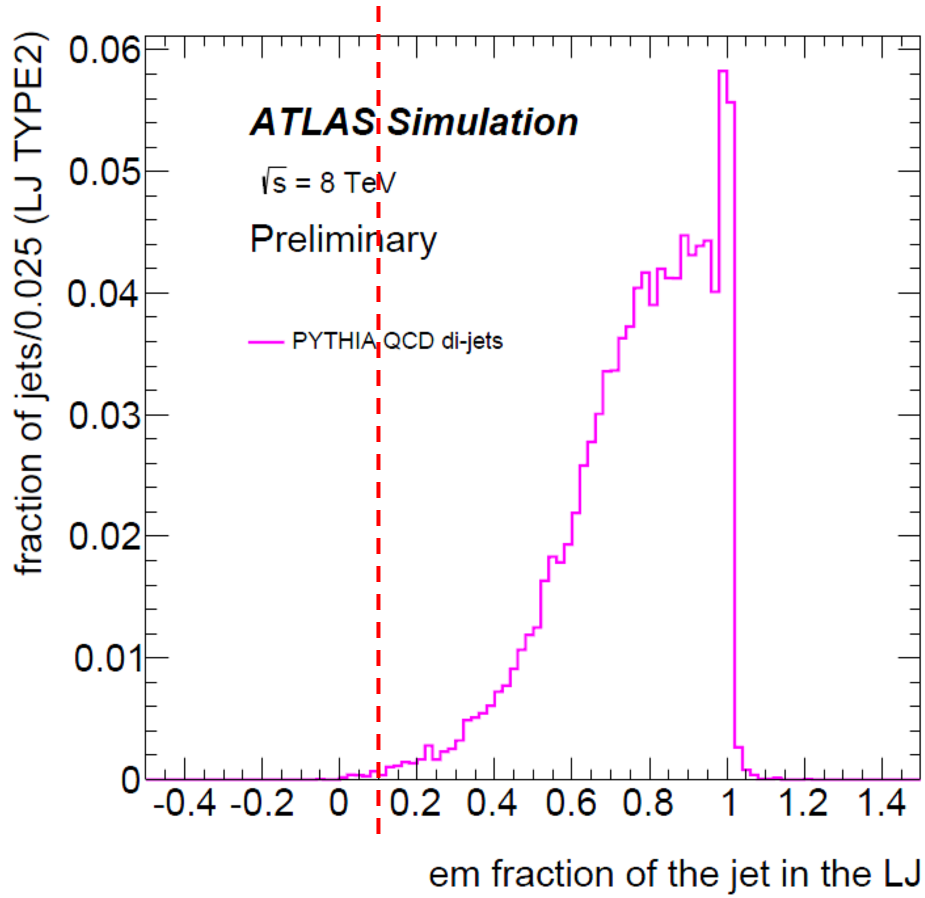
Single jet reconstruction efficiency $\sim 80\%$
NO difference in the two polarization states

Jets Energy Fraction in the EM Calorimeter



MC QCD di-jets



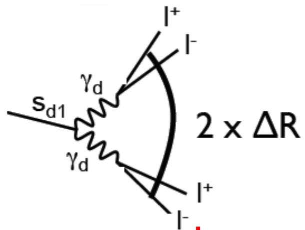


$$EM\ fraction < 0.1$$

$$\epsilon \gtrsim\ 70\ \%$$

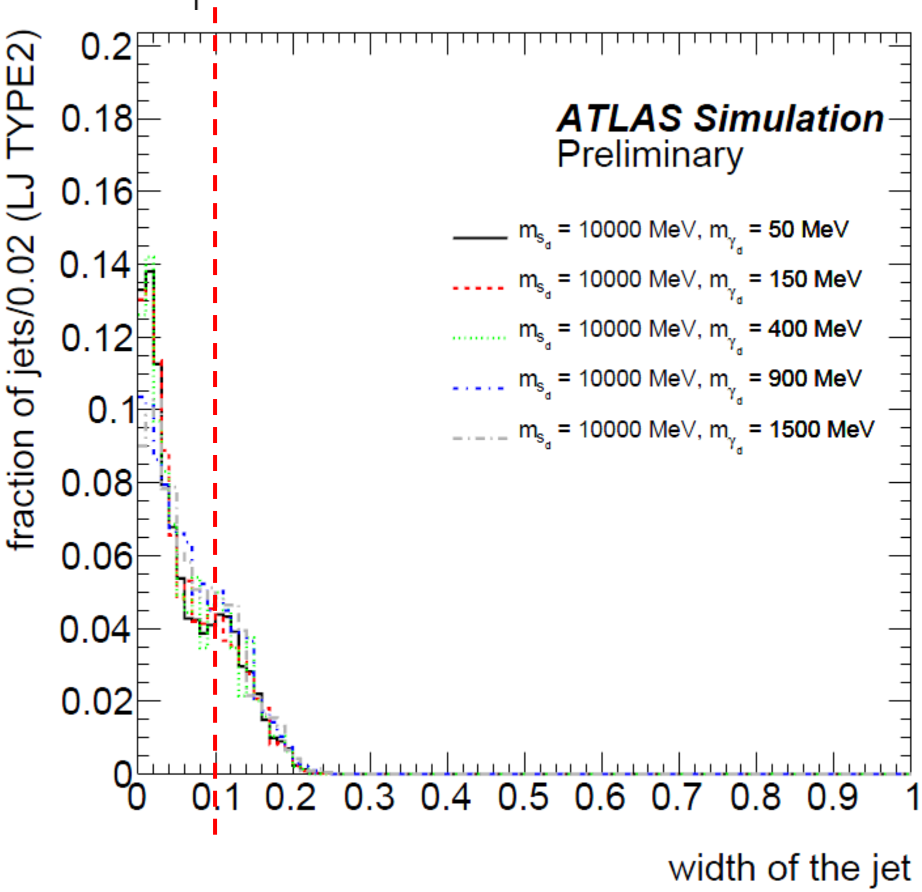
$$QCD\ di-jets\ removed \sim 99.9\%$$

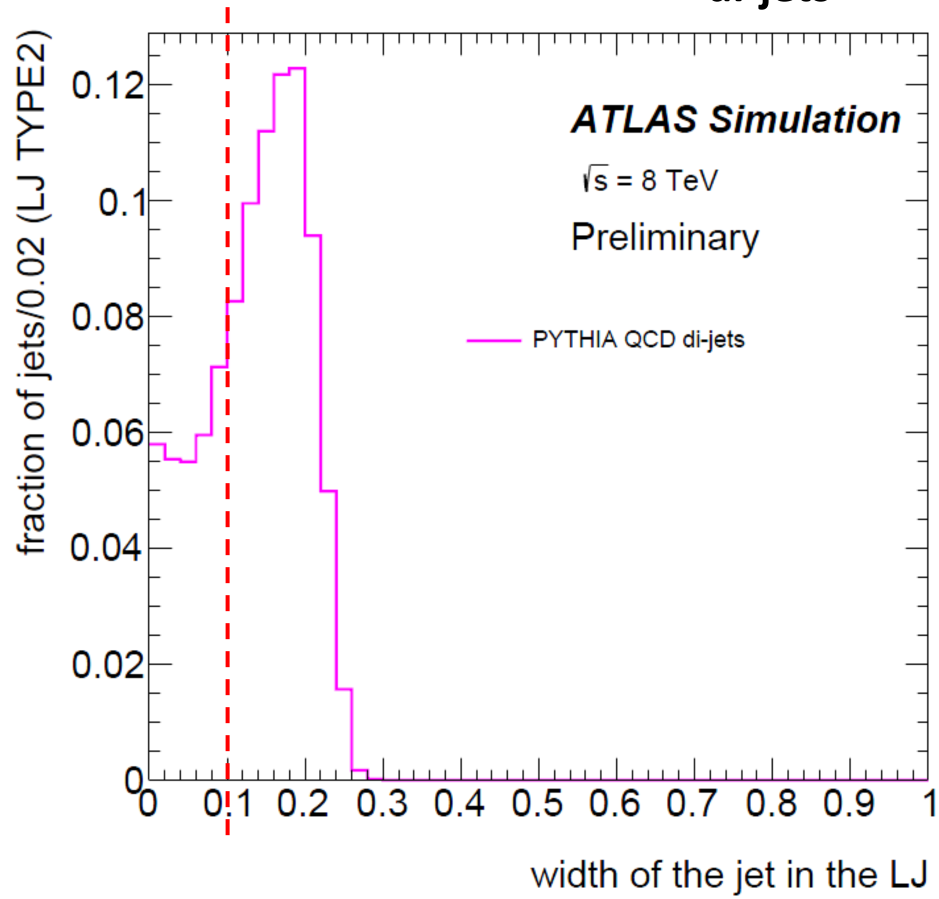
Jets Transverse Dimension (WIDTH)



$$WIDTH = \frac{\sum \Delta R(jet, constit) \cdot p_T constit}{\sum p_T constit}$$

MC QCD di-jets





$$WIDTH < 0.1$$

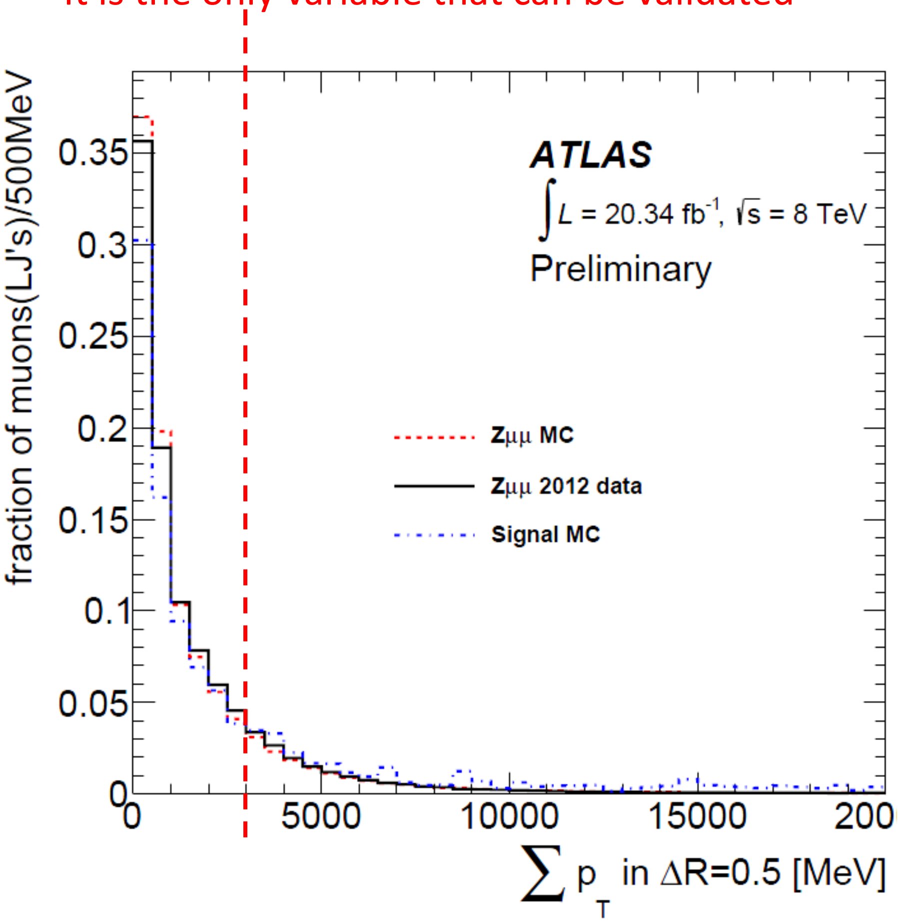
$$\epsilon \gtrsim 72\ \%$$

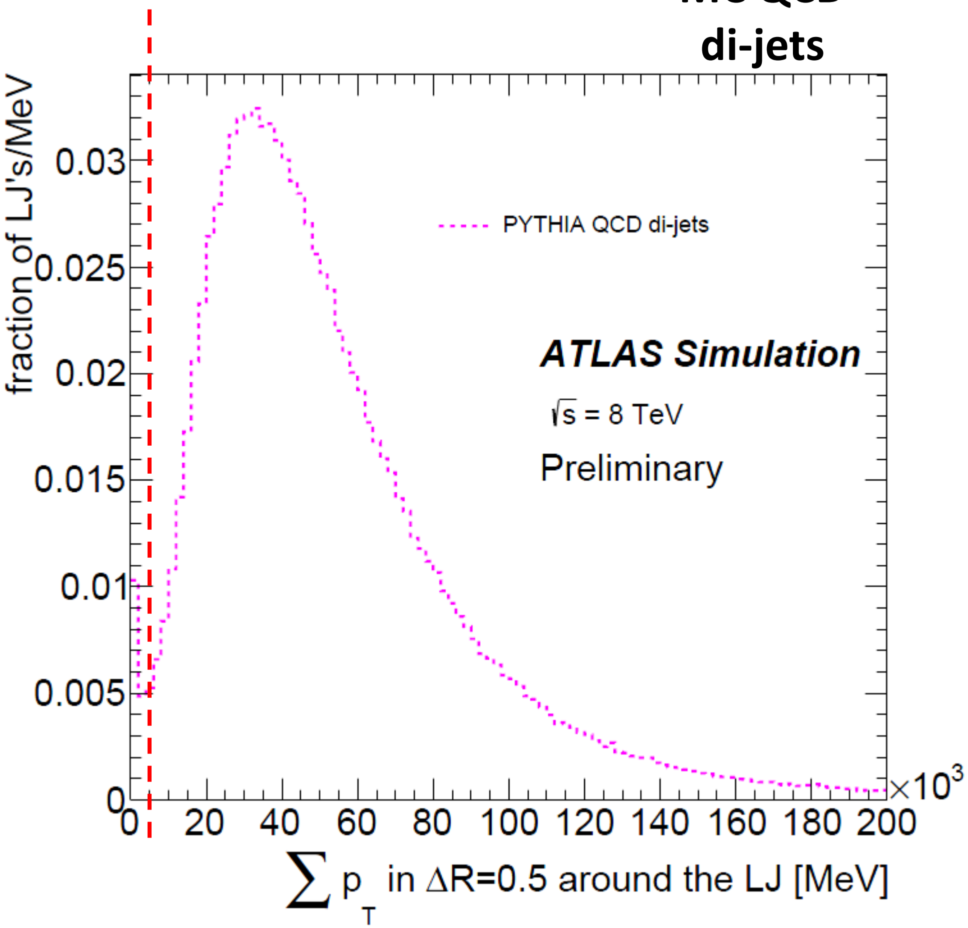
$$QCD\ di - jets\ removed \sim 77\%$$

Isolation $\sum p_T$

- Isolation variable $\sum p_T$ = scalar sum of the all tracks transverse momentum inside the Inner Detector in a cone of angular aperture equal to 0.5 around the Lepton Jet direction.
- It is the only variable that can be validated

MC QCD di-jets





$$\sum p_T < 3 \text{ GeV} \rightarrow \epsilon \sim 87\ \%$$

$$QCD\ di-jets\ removed \sim 99\%$$

Jet Timing

Timing t = time difference between the bunch crossing time and that relative to the energy deposition in the calorimetric cells

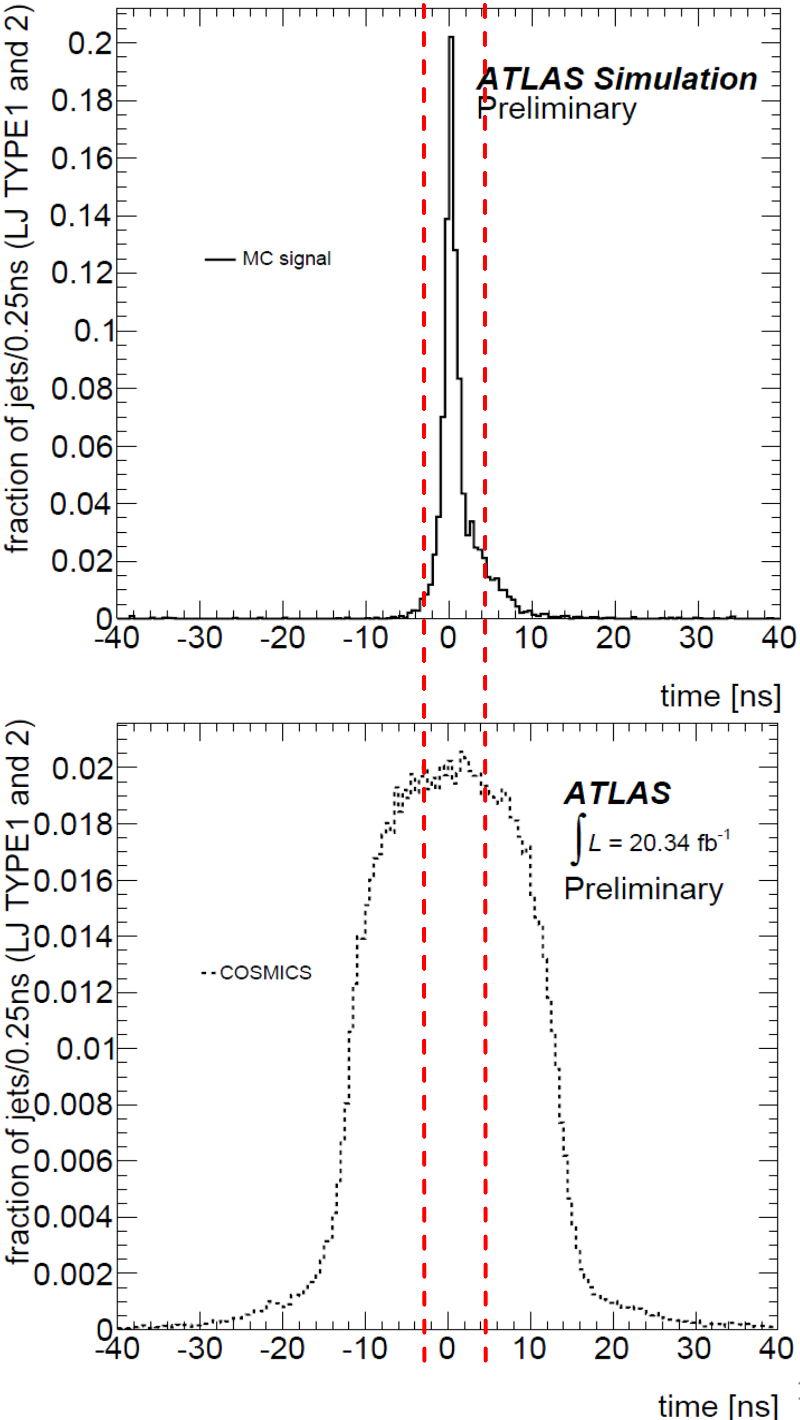
Remove jets with

$t < -1$ ns

o

$t > 5$ ns

$\epsilon \sim 85\ \%$
$cosmics\ removed \sim 75\%$

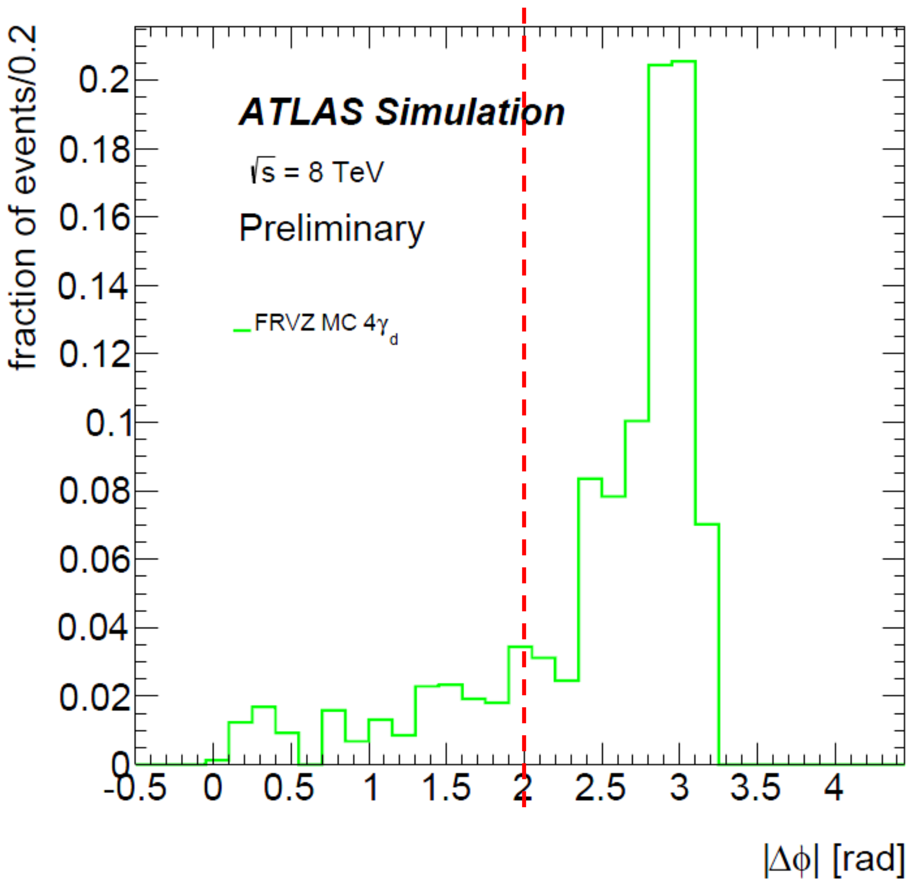


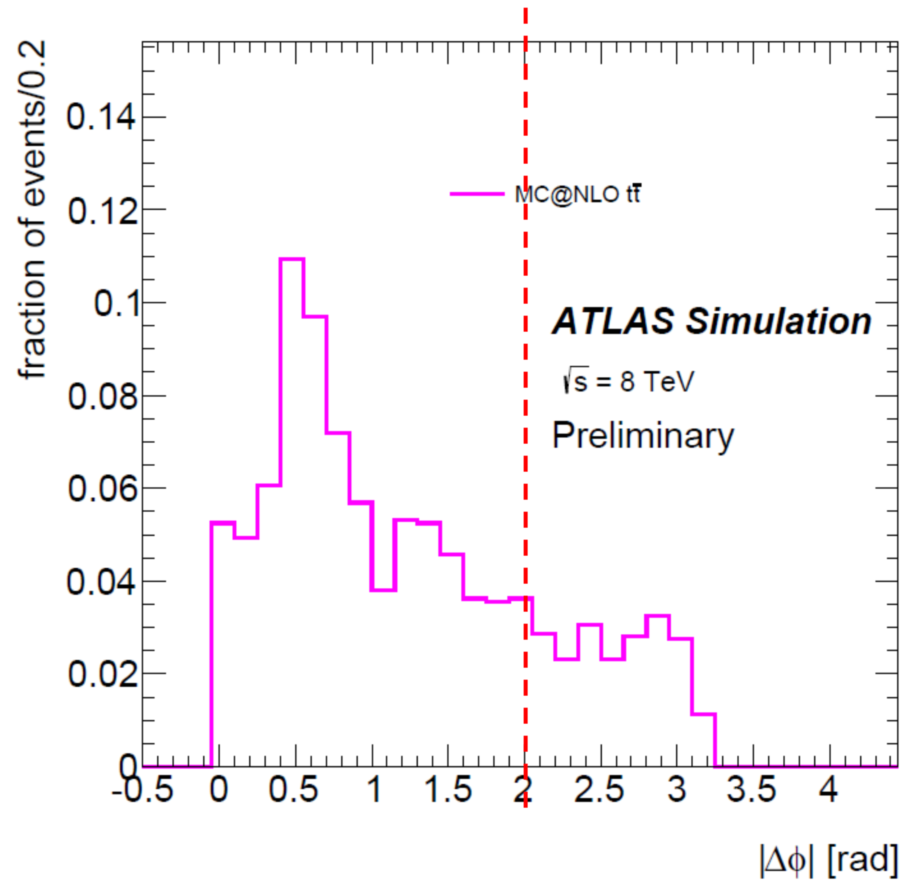
Lepton Jet Parameters

- Angular Aperture $\Delta R < 0.5$
- $EM\ fraction < 0.1$
- $WIDTH < 0.1$
- Isolation $\sum p_T < 3\ \mathrm{GeV}$
- Jet Timing $t \in [-1,5]$ ns

Additional cut at Event Level: Angulare Aperture between the two LJ in the event -$\Delta\phi$-

- Falkowsky-Ruderman-Volansky-Zupan Models (next slides) with two or four dark photons
- Background events $t - \bar{t}$
- $|\Delta\phi| > 2$ (Lepton Jets back-to-back production) to reduce the background





Lepton Jets Events Selection (cut flow)

cut	cut name	cut description
1	LJ minimal request	select events with at least 2 reconstructed LJ
2	η cut for LJ TYPE2	remove jets with $\lvert\eta\rvert > 2.2$ and $1.0 < \lvert\eta\rvert < 1.4$ (LJ TYPE2)
3	EM fraction cut for LJ TYPE2	require EM fraction of the jet < 0.1 (LJ TYPE2)
4	WIDTH cut for LJ TYPE2	require WIDTH of the jet < 0.1 (LJ TYPE2) < 0.1 (LJ TYPE2)
5	jet timing cut	require jets with timing $-1ns < t < 5ns$ (LJ TYPE1 and TYPE2)
Select the leading p_T LJ in the event and find the farthest LJ in $\lvert\Delta\phi\rvert$ wrt the leading LJ		
6	no combined muons	require no combined muons (LJ TYPE0 and TYPE1)
7	ID isolation	require $max(\sum p_T^{\Delta R<0.5}\ LJ1, \sum p_T^{\Delta R<0.5}\ LJ2) < 3000MeV$ (p_T tracks $>$ 500 MeV)
8	$\Delta\phi$ cut	require $\Delta\phi > 2\ rad$ between the two LJ's in the event (back-to-back production)

Background Events

- Background Events:
  - W/Z+jet and W/Z+jet+gamma
  - Di-photons and Di-bosons
  - Single top
  - $t - \bar{t}$
  - Cosmics
  - QCD di-jet

- All already negligible at trigger level, except for:
  - $t - \bar{t}$
  - Cosmics
  - QCD di-jet: too low MC statistics → ABCD method

Cut flow on $t - \bar{t}$ and cosmics

cut	Number of events MCNLO $t\bar{t}$
trigger selection	103880.0
good primary vertex	103840.0
LJ minimal request	11456.2
η cut for LJ TYPE2	580
EM fraction cut for LJ TYPE2	0
WIDTH cut for LJ TYPE2	0
jet timing cut	0
no combined muons	0
ID isolation	0
$\Delta\phi$ cut	0

No $t - \bar{t}$ events after the cut flow

cut	cosmic background (events from triggers on empty bunches)
trigger selection	161951
good primary vertex	-
LJ minimal request	11432
η cut for LJ TYPE2	7257
EM fraction cut for LJ TYPE2	7000
WIDTH cut for LJ TYPE2	4341
jet timing cut	80
no combined muons	80
ID isolation	80
$\Delta\phi$ cut	10

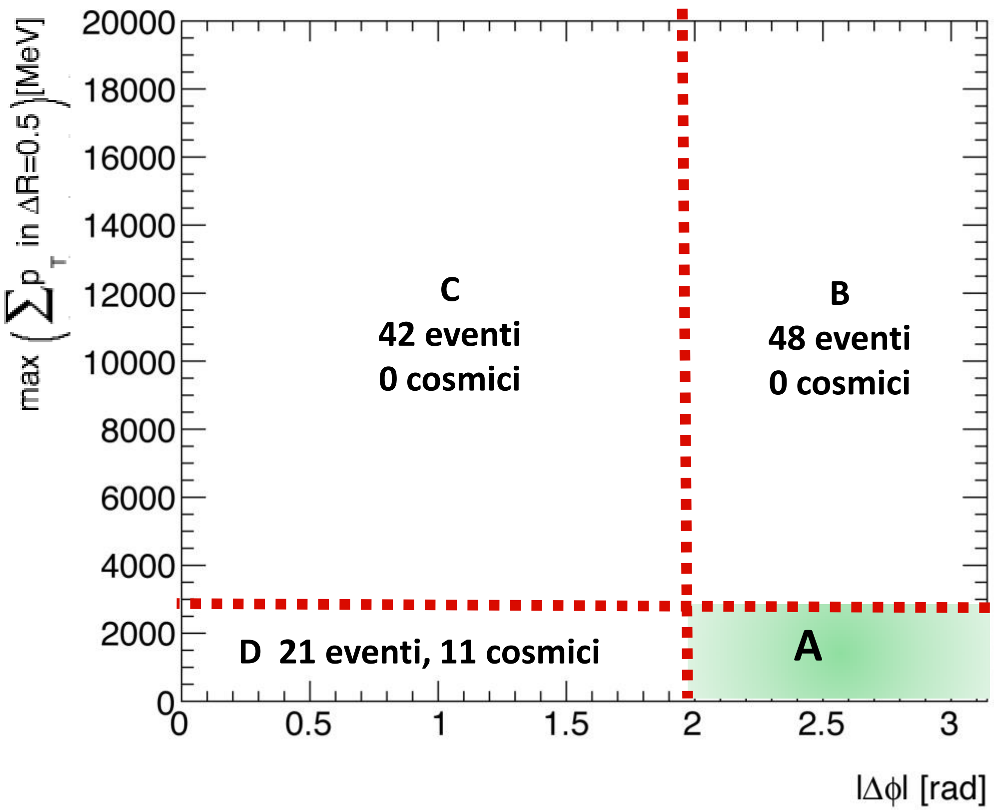
10 cosmics events after the cut flow

$$SF = \frac{Number\ of\ Filled\ Bunch\ Crossings}{Number\ of\ Empty\ Bunch\ Crossings}$$

Re-weighted cosmics = 23 ± 8

QCD background evaluation: ABCD method

- QCD di-jet: MC statistics too low → data driven technique → ABCD method
- Two variables ABCD method:
  background evaluation in the signal region (A) starting from the three control regions (BCD)
- Uncorrelated variables in this analysis: $\max \sum p_T$ e $|\Delta\phi|$



Signal Region:

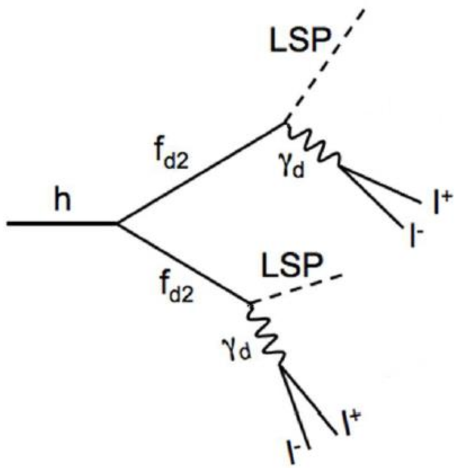
$$max \sum p_T < 3000 \text{ MeV AND } |\Delta\phi| > 2 \text{ rad}$$

$$\frac{N_A}{N_B} = \frac{N_D}{N_C} \rightarrow N_A = 48 * \frac{10}{42} = 11 \pm 8$$

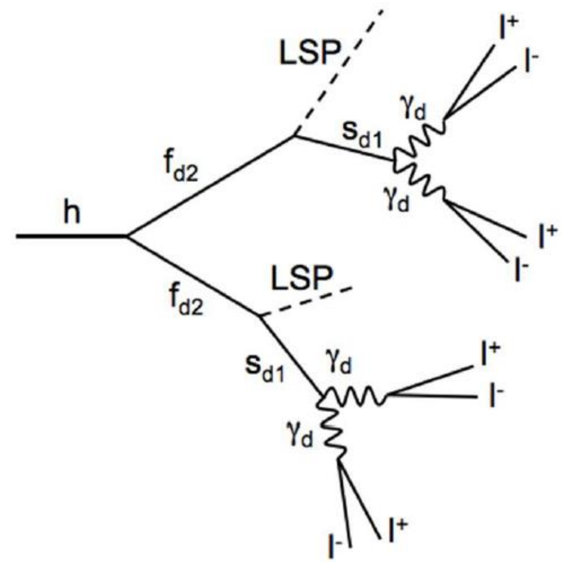
Hidden Valley Models (1)

Falkowsky-Ruderman-Volansky-Zupan **Models**

$2\gamma_d$ Model



$4\gamma_d$ Model



The Higgs boson is generated by gluon-gluon fusion.
In the proton-proton collision at $\sqrt{s} = 8\ \mathrm{TeV}$, the cross section for this process is $\sigma_{SM} = 19.3\ \mathrm{pb}$ for $m_H = 125\ \mathrm{GeV}$.

$m_{f_{d2}}$ $[GeV]$	$m_{f_{d1}/LSP}$ $[GeV]$	$m_{s_{d1}}$ $[GeV]$	m_{γ_d} $[GeV]$	$c\tau_{\gamma_d}$ [mm]	BR $\gamma_d \to ee$	BR $\gamma_d \to \mu\mu$	BR $\gamma_d \to \pi\pi$
5.0	2.0	-	0.4	47	0.45	0.45	0.10
5.0	2.0	2.0	0.4	47	0.45	0.45	0.10

Hidden Valley Models (2)

Higgs BR into the hidden sector = 10%, total luminosity = 20.34 fb^{-1}

cut	4 γ_d MC signal	2 γ_d MC signal
trigger selection	2518.1	1330.0
good primary vertex	2516.7	1329.8
η cut for LJ TYPE2	350.3	165.3
EM fraction cut for LJ TYPE2	240.1	111.0
WIDTH cut for LJ TYPE2	240.1	110.8
jet timing cut	226.1	105.3
no combined muons	123.5	67.6
ID isolation	84.6	52.7
$\Delta\phi$ cut	72.0	42.6

LJ pair type	4 γ_d MC signal	2 γ_d MC signal	cosmic bkg
0 - 0	27.0	16.1	12.6
0 - 1	28.4	7.0	0.0
0 - 2	2.2	8.4	10.7
1 - 1	11.7	1.0	0.0
1 - 2	2.7	1.1	0.0
2 - 2	0.0	9.0	2.9

Systematics

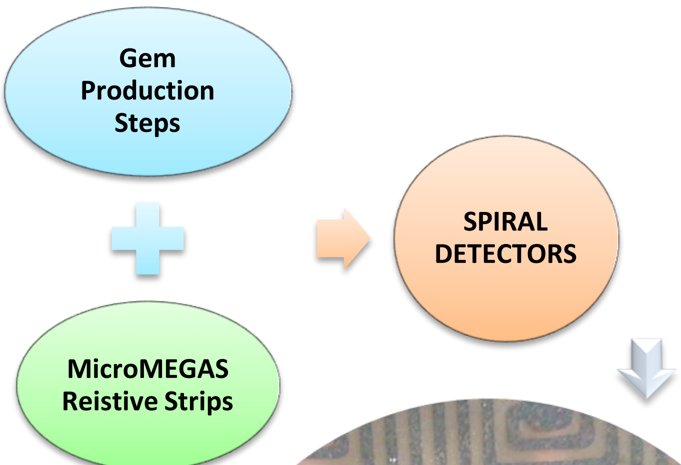
- Efficiency reconstruction systematics using $J/\Psi \rightarrow \mu^+\mu^-$ data → **5.4 %**
- Muonic trigger efficiency systematics using $J/\Psi \rightarrow \mu^+\mu^-$ data → **6 %**
- Calorimetric trigger efficiency systematics using 2012 data → **11%**
- Luminosity systematics: official value → **2.8 %**
- Higgs production cross section systematics → **15%**
- Effect of the pile-up on the isolation in ID → **2.5%**
- ABCD method systematics → **15 %**

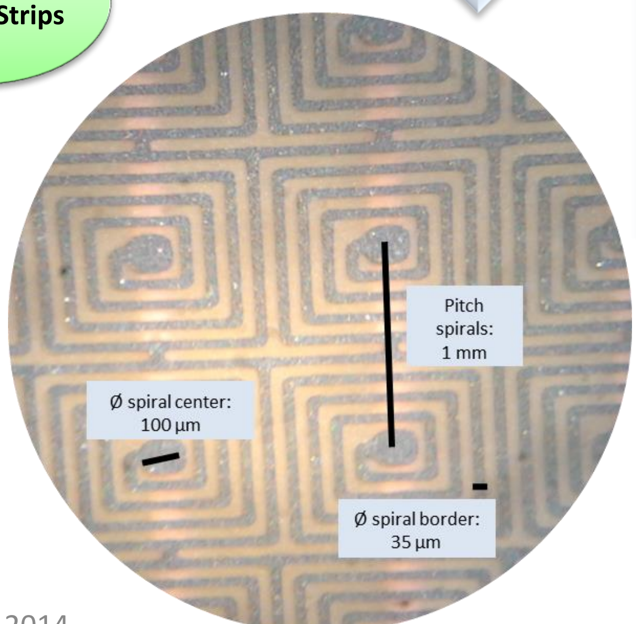
ANALYSIS NON YET UNBLINDED

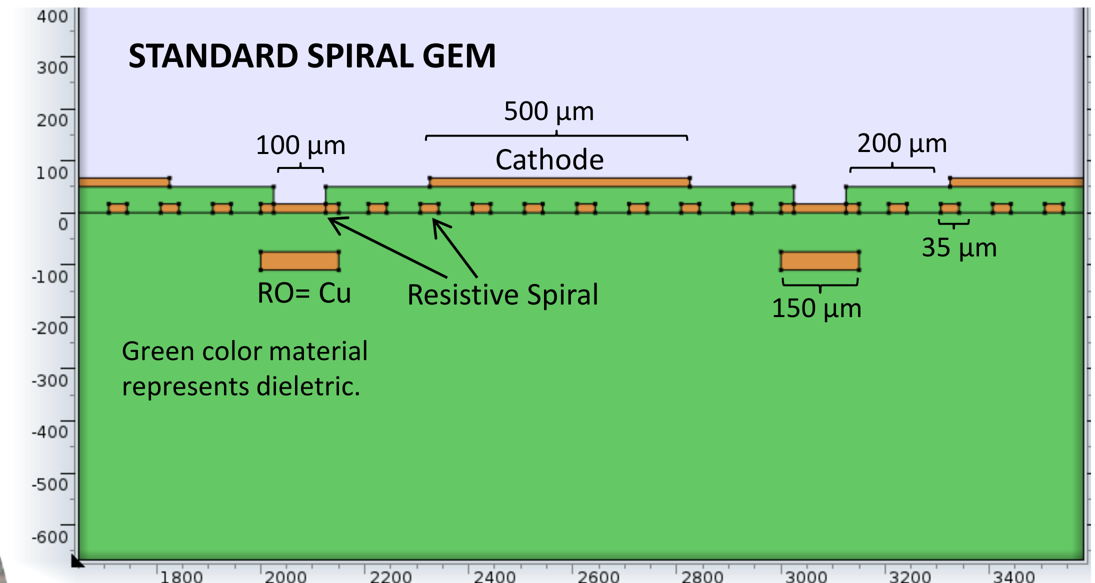
Micro-Pattern Gas Detectors: Spiral Detector

- Three months in the Rui De Oliveira workshop as CERN Summer Student
- Hardware R&D project: simulate, optimize and produce Micro-Pattern Gas Detectors
- Two main important items: Spiral Detector and Conic ThGEM (see report at https://cds.cern.ch/record/1603668)

WHAT ABOUT SPIRAL DETECTOR?







After this first version, other two improvements of the spiral detector were produced (see extra slides for detail)

Micro-Pattern Gas Detectors: Spiral Detector

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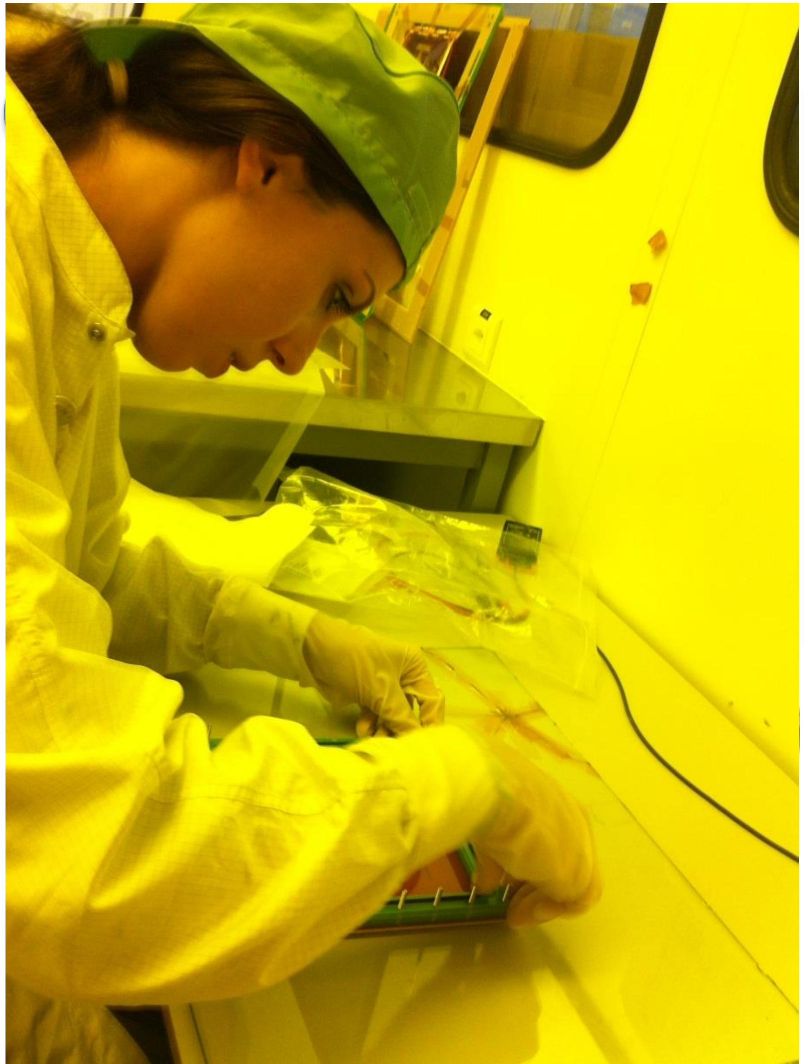
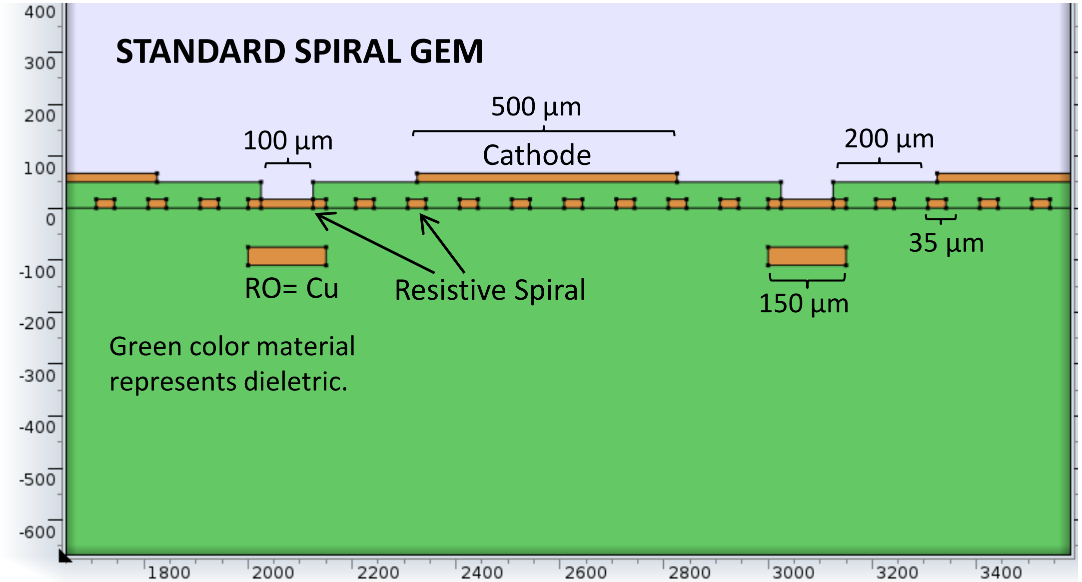




After this first version, other two improvements of the spiral detector were produced (see extra slides for detail)

Results & Conclusions

ANALYSIS

Lepton Jets production can occur through a rare Higgs decay in hidden particles. Some of these particles (dark photons) can be long lived particles and decay into collimated pairs of light visible particles.

Useful references

kinetic mixing:

- B. Holdom, *Phys.Lett. B166 (1986) 196*

lepton jet idea:

- N. Arkani-Hamed and N. Weiner, 0810.0714

lepton jet pheno:

- M. Baumgart C. Cheung, J.T. Ruderman, L.-T. Wang, I. Yavin, 0901.0283
- Y. Bai, Z. Han, 0902.0006
- C. Cheung, J.T. Ruderman, L.-T. Wang, I. Yavin, 0909.0290
- A. Falkowski, J.T. Ruderman, T. Volansky, J. Zupan, 1002.2952
- A. Falkowski, J.T. Ruderman, T. Volansky, J. Zupan, 1007.3496
- L. Carloni, J. Rathsman, T. Sjostrand, 1102.3795
- Y. F. Chan, M. Low, D. E. Morrissey, A. P. Spray, 1112.2705

State of the Art when I defended my thesis:

- Lepton Jet Gun Monte Carlo to define cut flow
- Cut flow on background events: 11 QCD di-jets and 23 cosmics
- Cut flow on FRVZ Models: 72 events in the 4gds model and 43 events in the 2gds model
- Systematics evaluated
- Ready for the first meeting with the Editorial Board

State of the Art now:

- After a long discussion with the Editorial Board → $|\Delta\phi| > 1$ instead of $|\Delta\phi| > 2$ (more model independent)

Ready for the approval and the unblinding (ATL-COM-PHYS-2014-028 at https://cds.cern.ch/record/1643479)

HARDWARE

The first version of the Spiral Detector was presented at the 12th RD51 Collaboration Meeting (https://indico.cern.ch/conferenceTimeTable.py?confId=267513#20131016) in October 2013 at CERN, and at the XII workshop on Resistive Plate Chambers and Related Detectors (http://166.111.32.59/indico/contributionDisplay.py?contribId=62&sessionId=30&confId=1) in February 2014 in Beijing.

The last improvement of the spiral detector is under test.

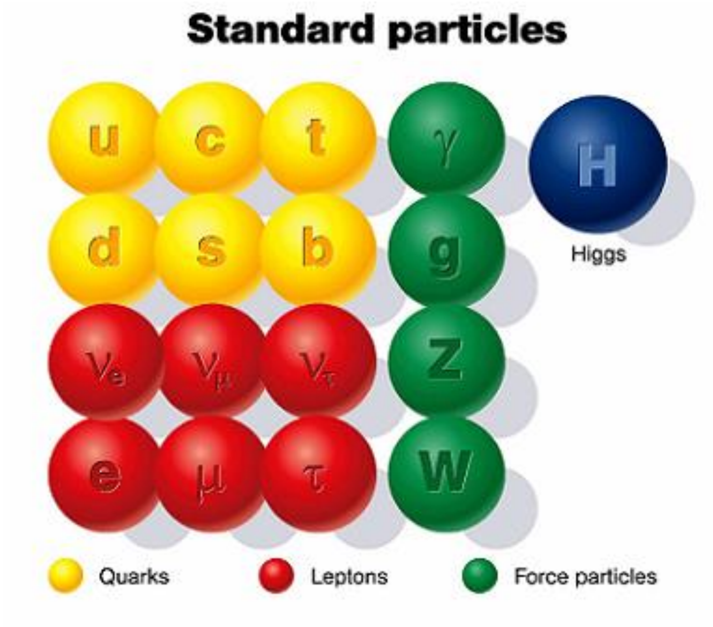
Thanks for your attention!

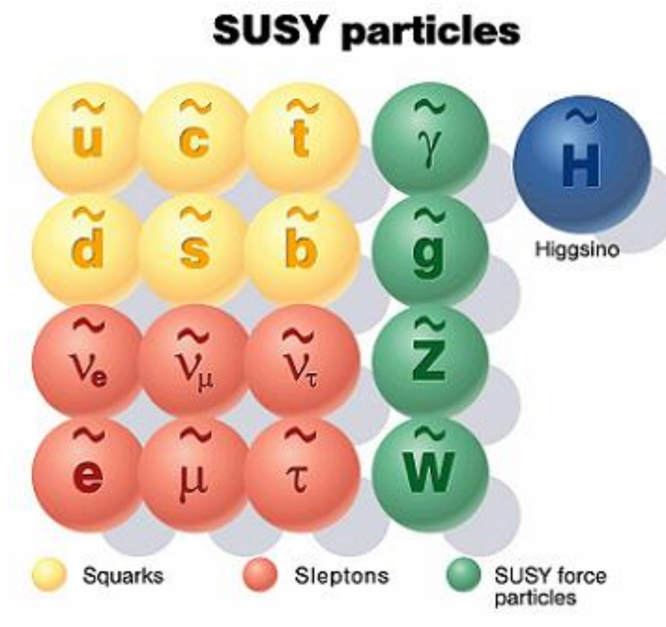
Pensare per il piacere di pensare,
come per la musica…
Albert Einstein

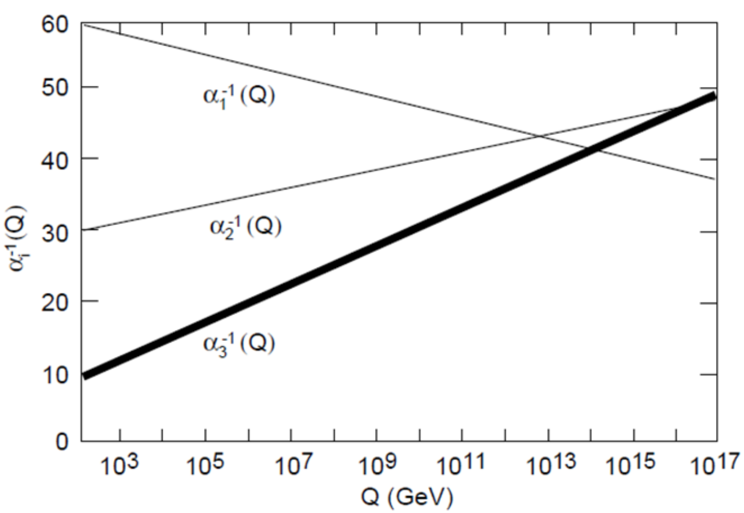
Valentina Cairo
March 17th 2014

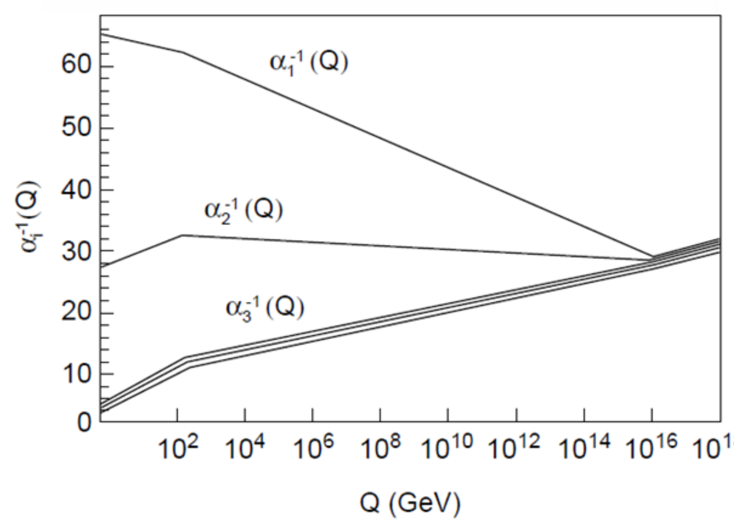
EXTRA SLIDES

Standard Model and Supersymmetry



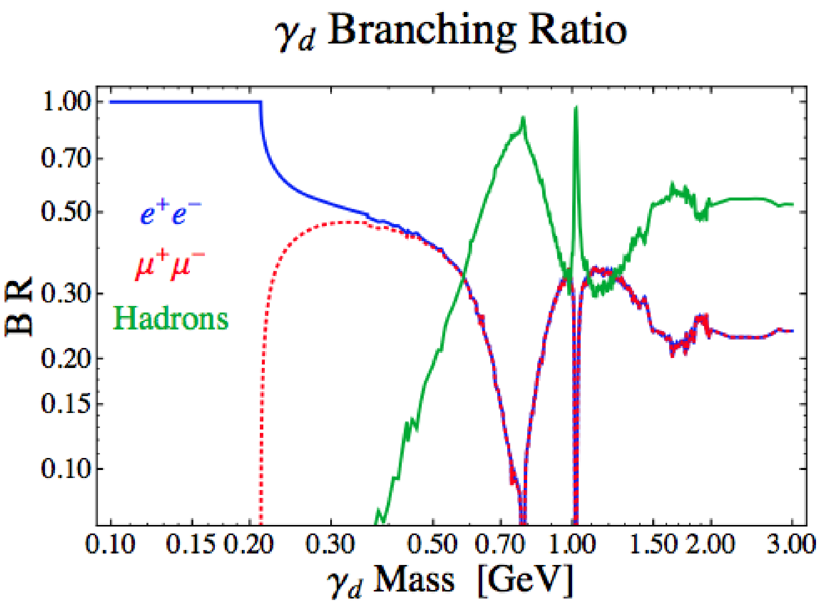






Not yet supersymmetric particles observed

Composition and lifetime

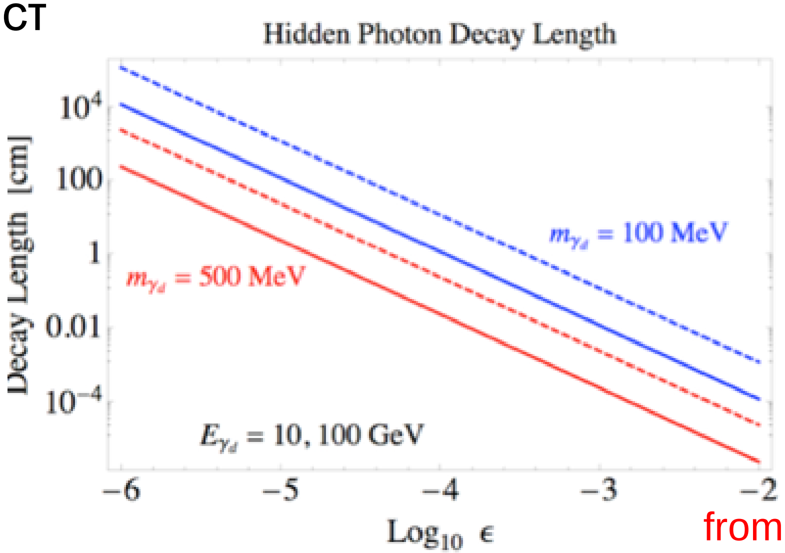


composition depend on dark photon mass:

- $m_\gamma < 2m_e \rightarrow$ dark photon stable $\rightarrow$ invisible higgs signature
- $2m_e < m_\gamma < 2m_\mu \rightarrow$ electron-jets
- $2m_\mu < m_\gamma < 2m_\pi \rightarrow$ electron&muon-jets
- $m_\gamma > 2m_\mu \rightarrow$ pion-jets (BR depends on R)

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

CT



lifetime depends on the size of kinetic mixing:

$$\Gamma = \frac{1}{3}\alpha\,\epsilon^2\, m_{\gamma_d}\sqrt{1-\frac{4m_l^2}{m_{\gamma_d}^2}}\left(1+\frac{2m_l^2}{m_{\gamma_d}}\right)$$

NOTE: due to the low γ_d mass, boost also important

from prompt decays to decays into any part of the ATLAS detector

Dark Matter Experimental Evidences

NGC 4911 spiral galaxy into the Coma Cluster.

Fritz Zwickly , 1933:
Coma Cluster galaxies were moving too quickly with respect their visible mass.

Canada–France–Hawaii telescope situated on the Mauna Kea mountain at 4.204 m.

Telescopio Canada-Francia-Hawaii, 2008*:*
The light has a deviation during its cosmic journey also where there is no visible mass.

PAMELA (a Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics), sent into the space on the Resurs-DK1 satellite.

PAMELA, in orbit around the Earth from 2006:
It measured an increase of the ratio $\mathrm{e}^{+}/(e^{+}+e^{-})$ into the range $10-50$ GeV.
A possible explaination is the annihilation of Dark Matter:
WIMPs can collide with annihilation into a photon that materialize into a electron-positron pair.

Quality Criteria for MS and ID tracks

MS tracks

- $p < 1\text{TeV}$; $|\phi| < 5\text{rad}$; $|z_0| < 270\text{mm}$; $|d_0| < 200\text{mm}$;
- nMDThits $> 9 \cap$ (nRPCPhiHits+nRPCEtaHits) > 2 per il barrel;
- nMDThits $> 9 \cup$ (nCSCPhiHits + nCSCEtaHits > 2) $\cap$ (nTGCPhiHits + nTGCEtaHits) > 2 per gli endcap.

ID tracks

- $|z_0| < 10\text{mm} \cap \mathrm{p_T} > 500\text{MeV} \cap |\eta| < 2.4$;
- nBLhits $> 0 \cap$ nPixHits $> 1 \cap$ nSCThits $> 5 \cap$ nTRThits > 5.

Available MC generators in ATLAS

- Displaced-LJ generator based on MG5 (FVRZ)
  - 2 and 4 dark photons (can be generalized to more γ_d)
  - interfaced with ATLAS via lha input files
  - parameters: h, N, n, LVSP, γ_d masses, γ_d lifetime

- LJ Gun generator: very useful to build up acceptance/efficiency maps as a function of the above parameters
  - reduce model dependence in optimizing the analysis selection
  - facilitate interpretation in the context of different models

Non-prompt LJs

TYPE 0: ≥ 2 MUIDSA clustered in a $\Delta R=0.5$ cone and NO jets in the cone

TYPE 1: ≥ 2 MUIDSA + one "good" jet clustered in a $\Delta R=0.5$ cone

TYPE 2: a jet with EM fraction < 0.4 and width <0.2

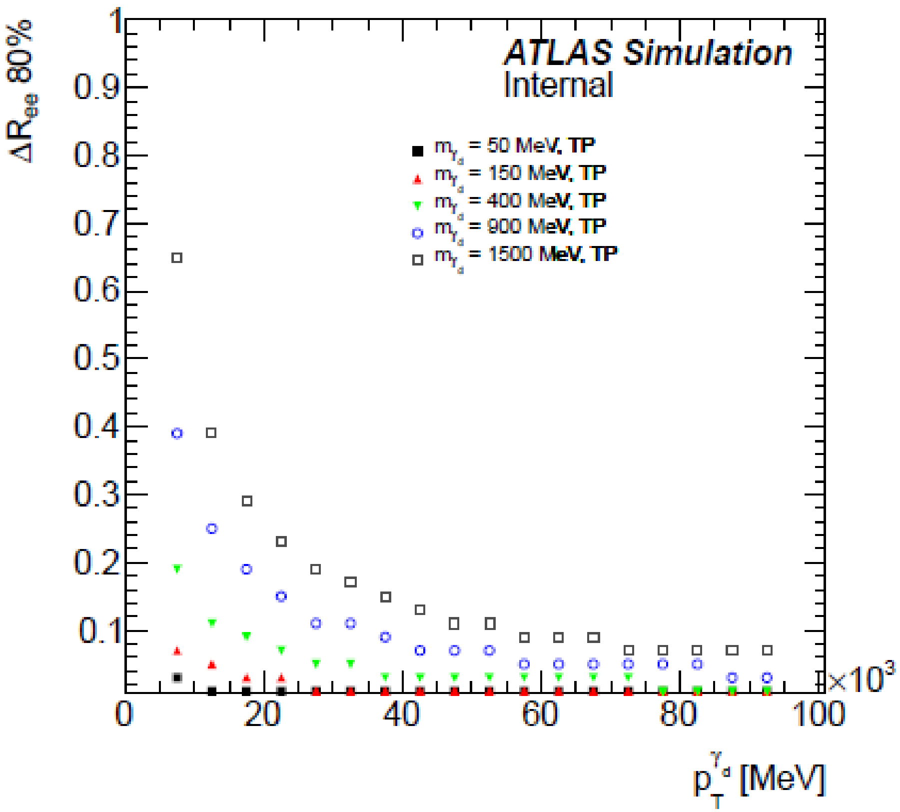
Lepton Jet Gun Monte Carlo (2)

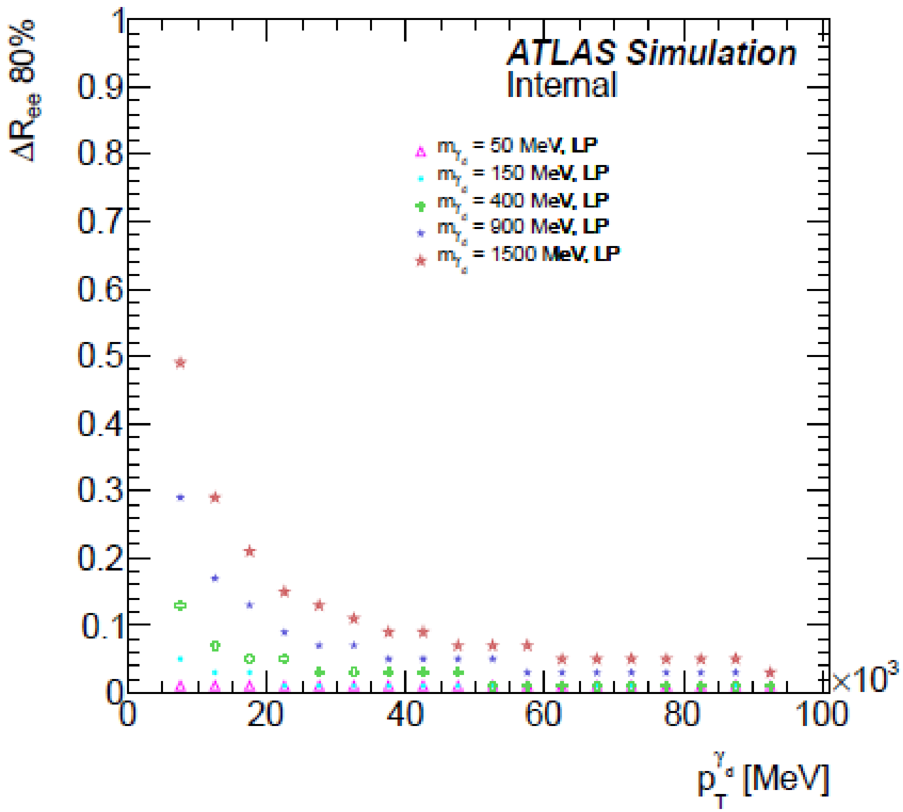
MC12 dataset ID	m_{γ_d} [MeV]	γ_d polarization	BR $\gamma_d \to e^+e^-$	BR $\gamma_d \to \mu^+\mu^-$	BR $\gamma_d \to \pi^+\pi^-$
182483	50	TP	1	0	0
182483	50	LP	1	0	0
182487	150	TP	1	0	0
182488	150	LP	1	0	0
182491	400	TP	0.45	0.45	0.10
182492	400	LP	0.45	0.45	0.10
182495	900	TP	0.30	0.30	0.40
182496	900	LP	0.30	0.30	0.40
182499	1500	TP	0.30	0.30	0.40
182500	1500	LP	0.30	0.30	0.40

Lepton Jet Gun Monte Carlo (3)

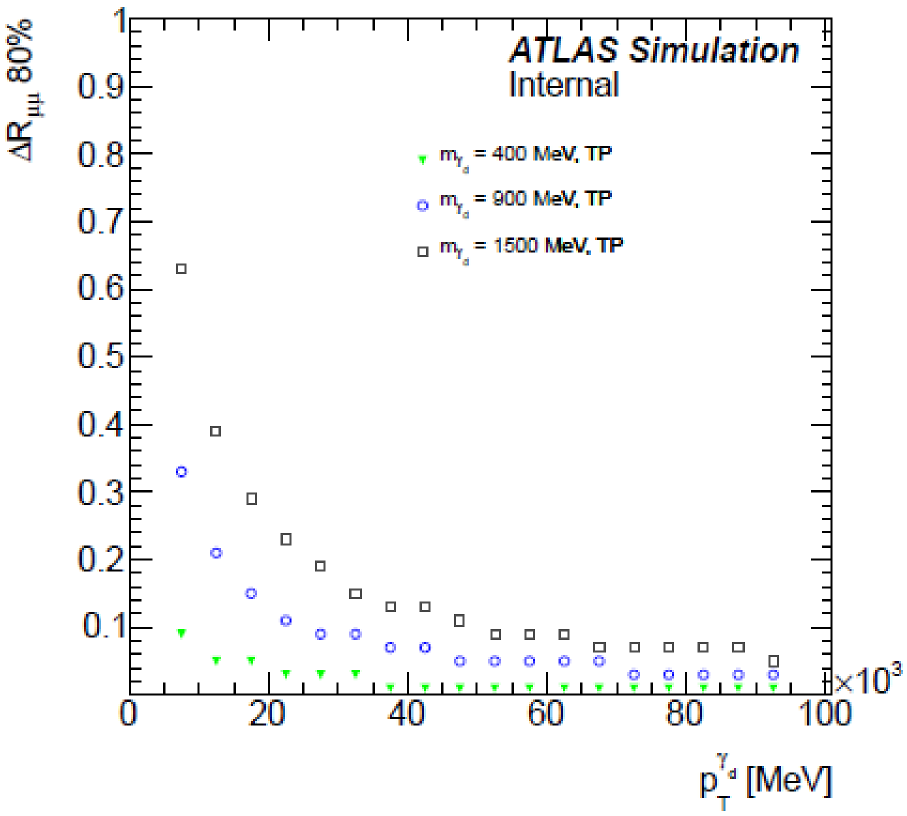
MC12 dataset ID	$m_{s_{d1}}$ [GeV]	${p_T}^{s_{d1}}$ [GeV]	m_{γ_d} [MeV]	BR $\gamma_d \to e^+e^-$	BR $\gamma_d \to \mu^+\mu^-$	BR $\gamma_d \to \pi^+\pi^-$
182502	1	5÷100	50	1	0	0
182504	1	5÷100	150	1	0	0
182506	1	5÷100	400	0.45	0.45	0.10
182508	2	5÷100	50	1	0	0
182510	2	5÷100	150	1	0	0
182512	2	5÷100	400	0.45	0.45	0.10
182514	2	5÷100	900	0.30	0.30	0.40
182516	5	10÷100	50	1	0	0
182518	5	10÷100	150	1	0	0
182520	5	10÷100	400	0.45	0.45	0.10
182522	5	10÷100	900	0.30	0.30	0.40
182524	5	10÷100	1500	0.30	0.30	0.40
182526	10	15÷100	50	1	0	0
182528	10	15÷100	150	1	0	0
182530	10	15÷100	400	0.45	0.45	0.10
182532	10	15÷100	900	0.30	0.30	0.40
182534	10	15÷100	1500	0.30	0.30	0.40

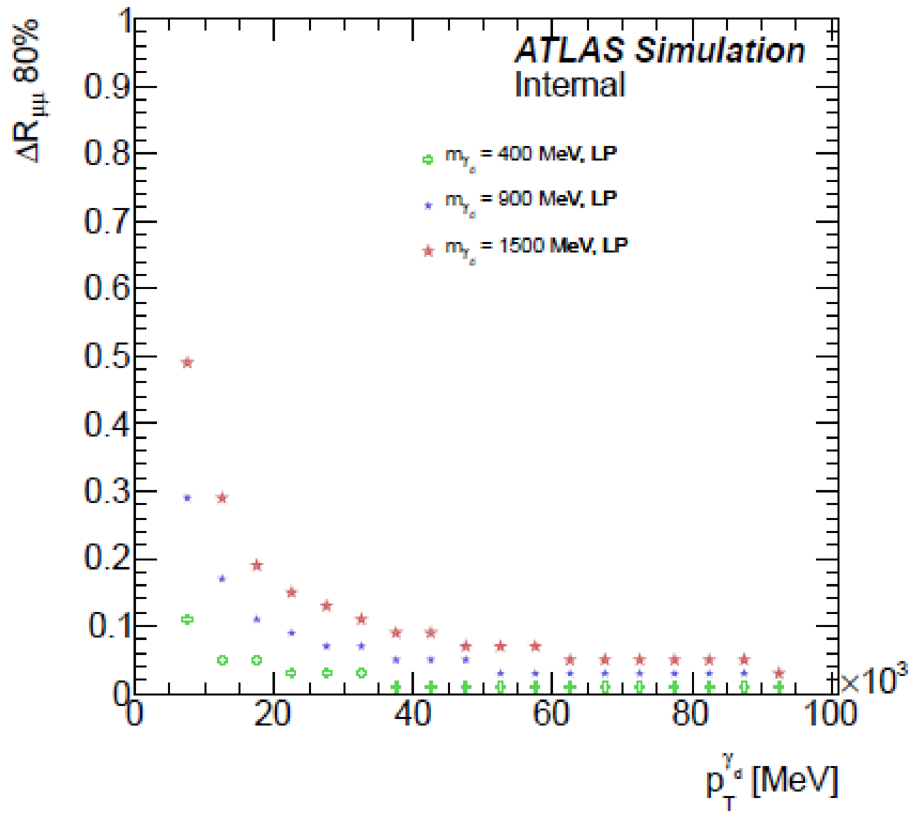
Lepton Jet Gun $\Delta R_{80\%}$ $\gamma_d \rightarrow e^+e^-$



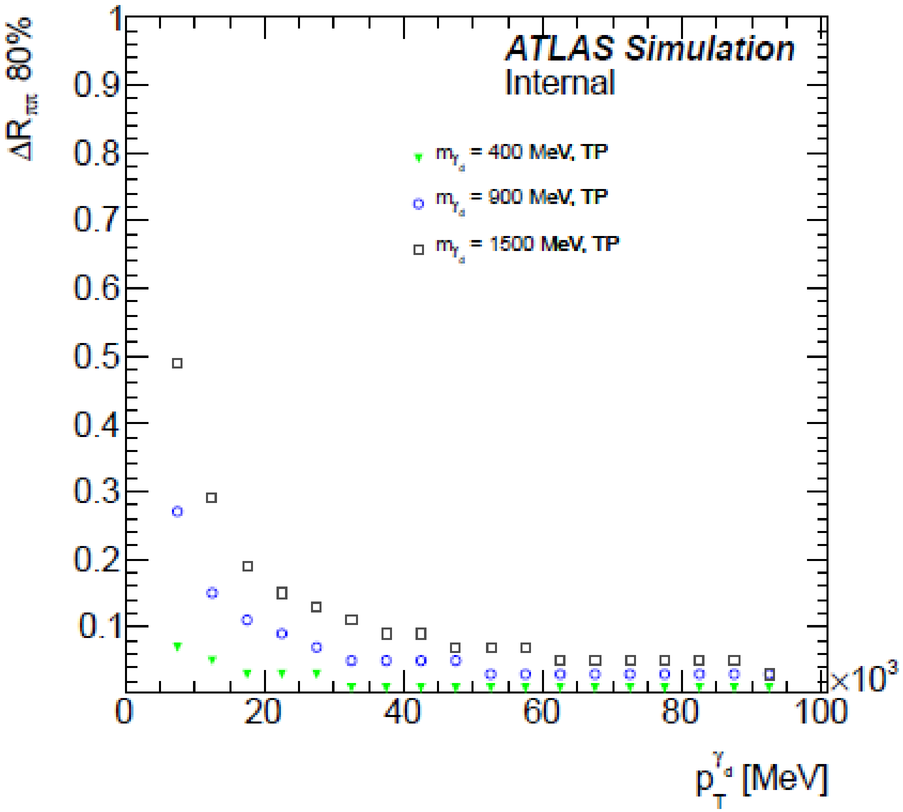


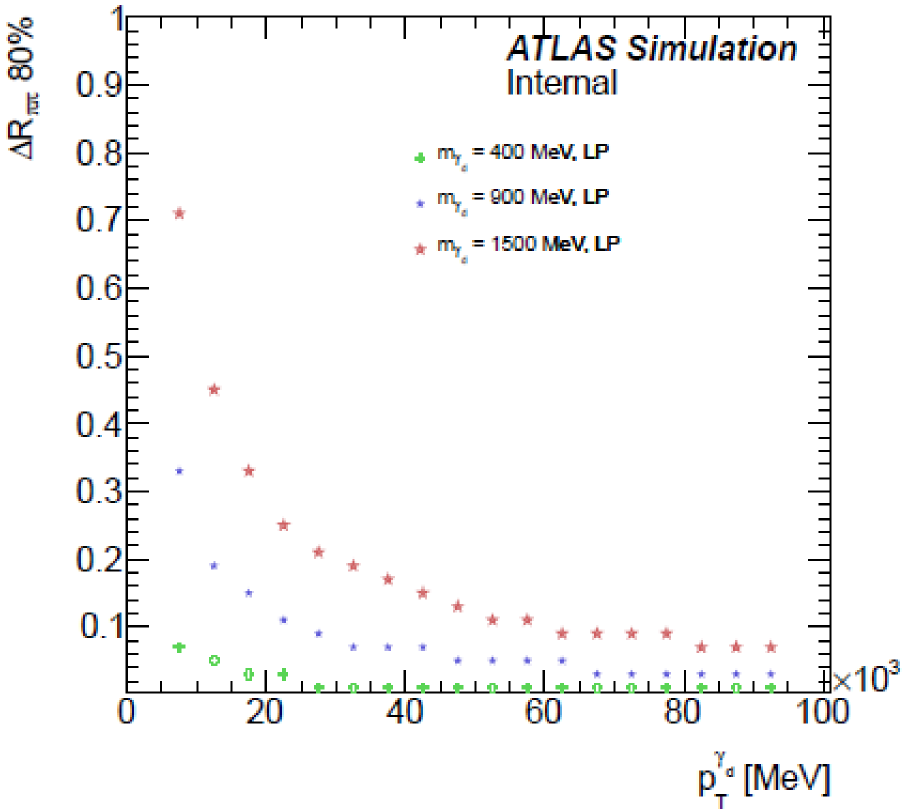
Lepton Jet Gun $\Delta R_{80\%}\ \gamma_d \rightarrow \mu^+\mu^-$



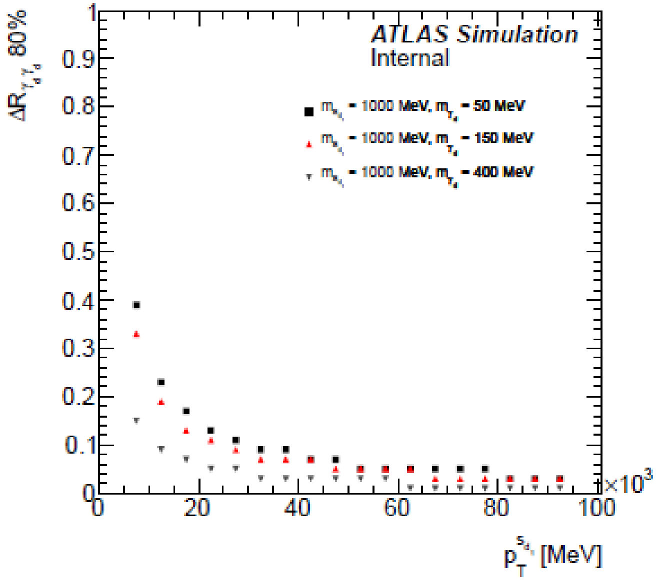


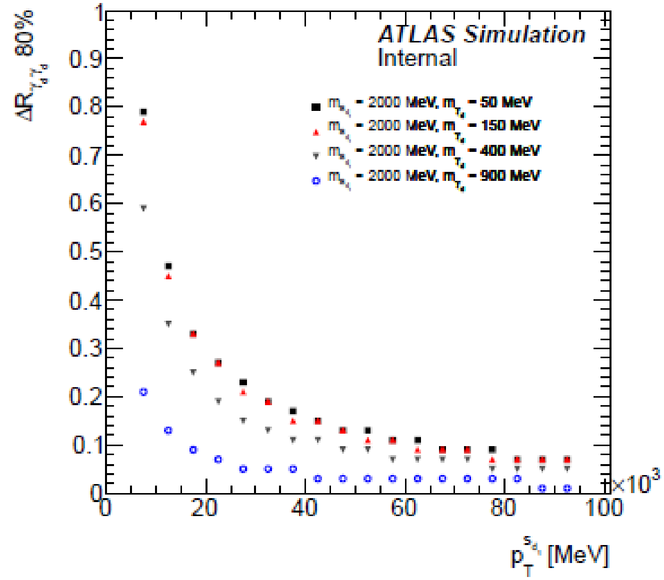
Lepton Jet Gun $\Delta R_{80\%}$ $\gamma_d \rightarrow \pi^+\pi^-$

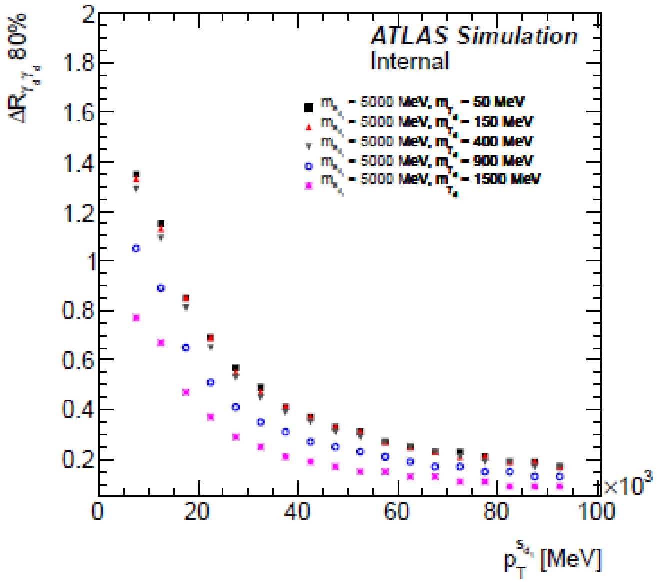


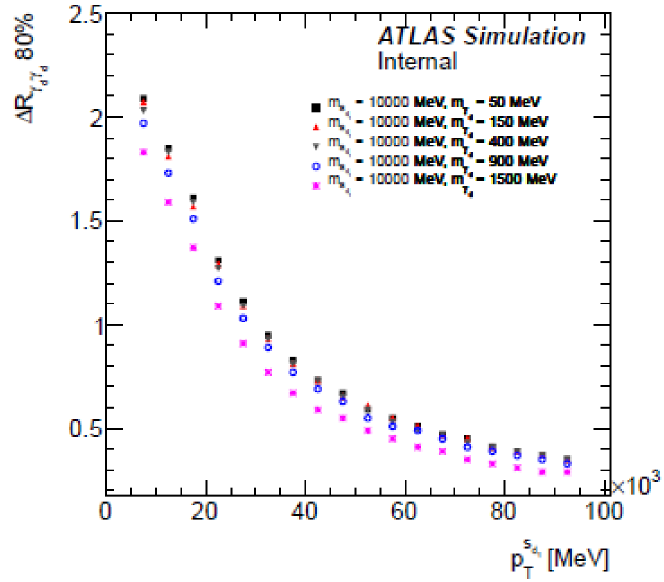


Lepton Jet Gun $\Delta R_{80\%}$ $s_d \rightarrow \gamma_d\gamma_d$









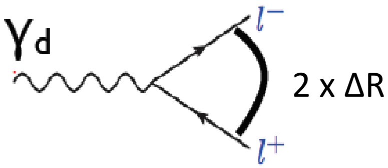
Lepton Jet Gun: Reconstruction Efficiency

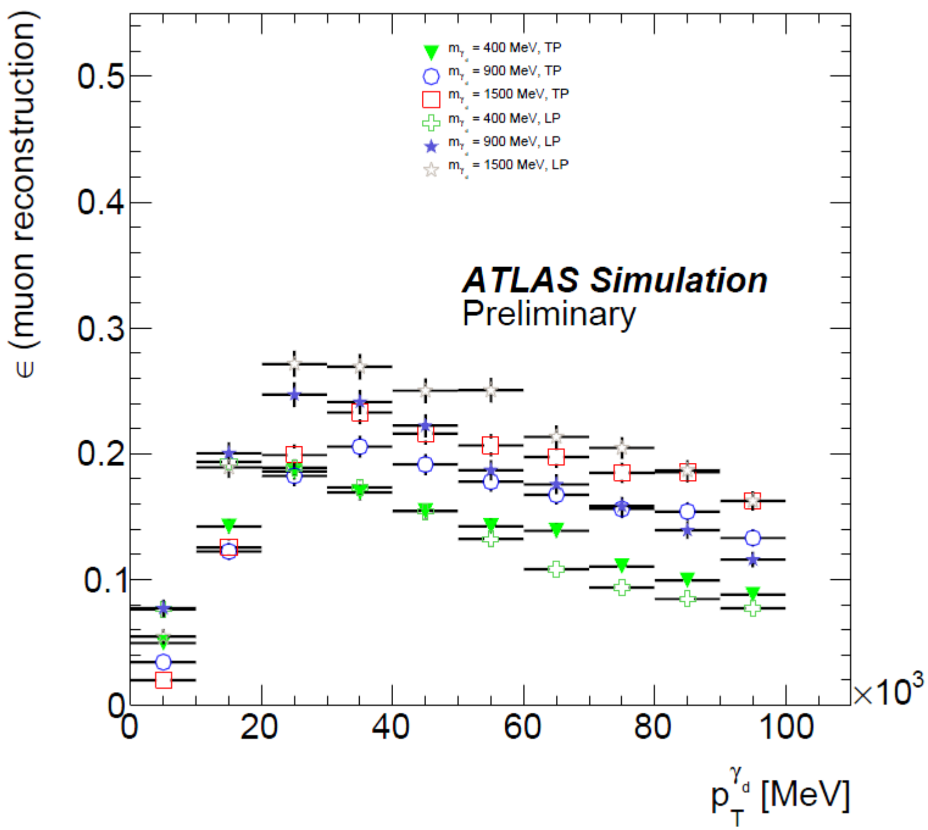
- Lepton Jet Gun Monte Carlo to evaluate the Lepton Jets reconstruction efficiency

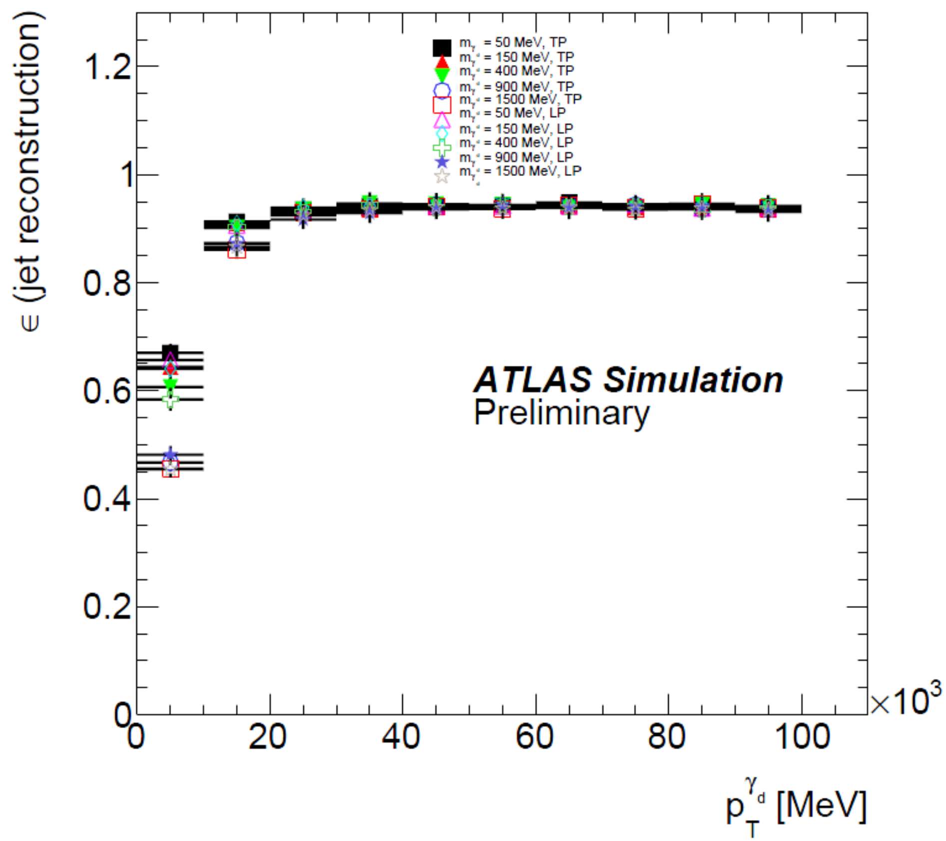
The reconstruction efficiency is defined as:

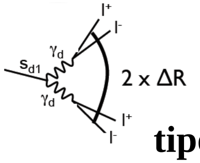
$$\epsilon_{rec} = \frac{\#LJ_{rec}}{\#_{tot}LJ_{GunMC}}$$

Reconstruction Efficiency for muons and jets VS p_T



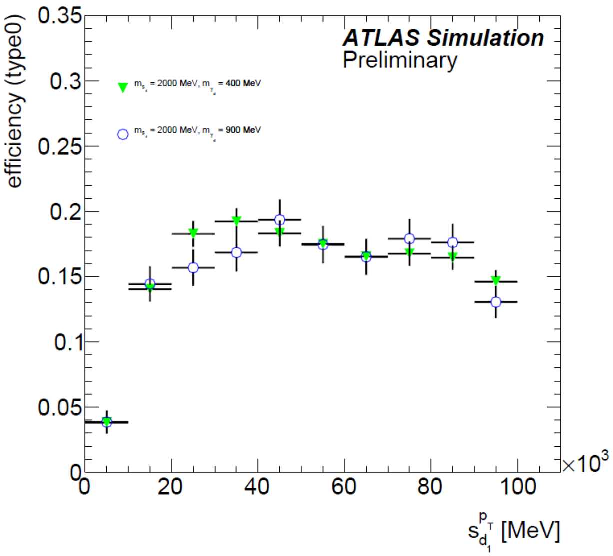




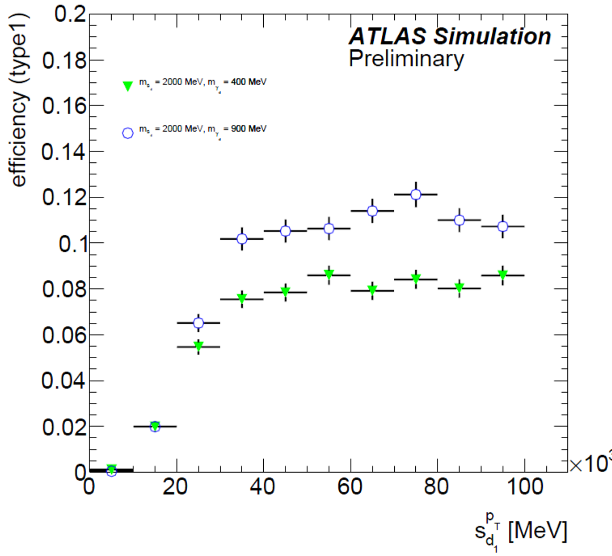


Reconstruction Efficiency for LJ VS p_T

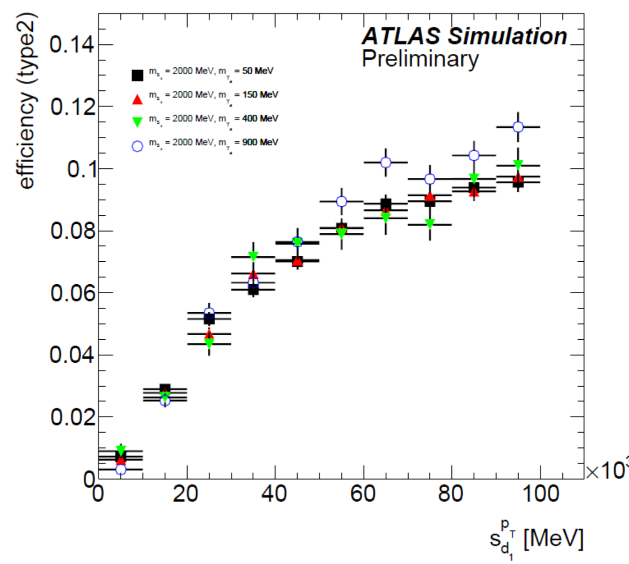
tipo 0, $m_{sd_1} = 2$ GeV



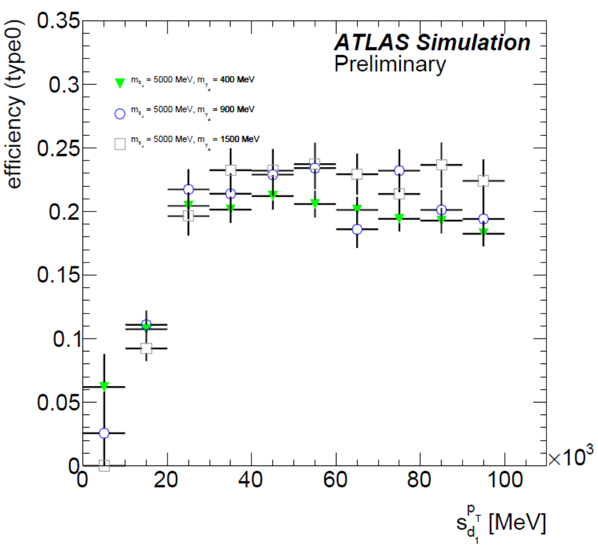
tipo 1, $m_{sd_1} = 2$ GeV



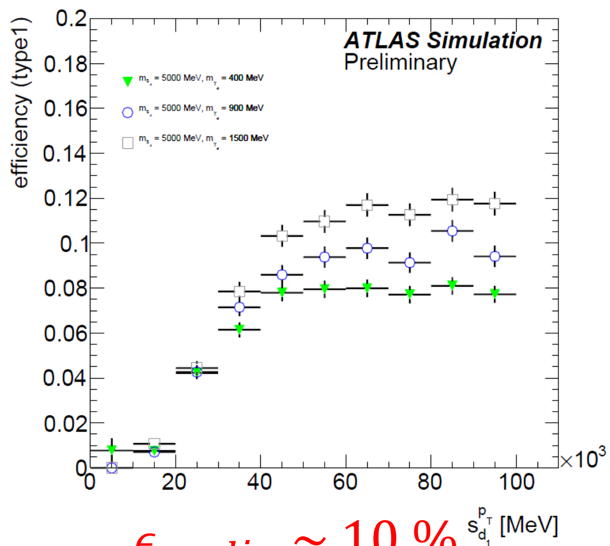
tipo 2, $m_{sd_1} = 2$ GeV



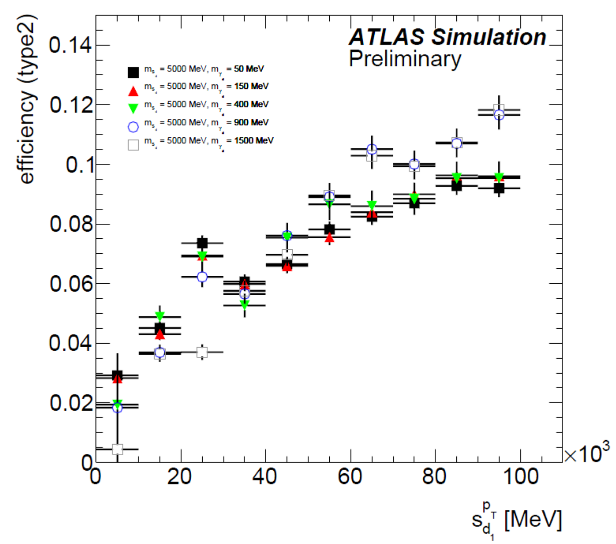
tipo 0, $m_{sd_1} = 5$ GeV



tipo 1, $m_{sd_1} = 5$ GeV



tipo 2, $m_{sd_1} = 5$ GeV



$\epsilon_{media} \sim 10\ \%$

Reconstruction Efficiency

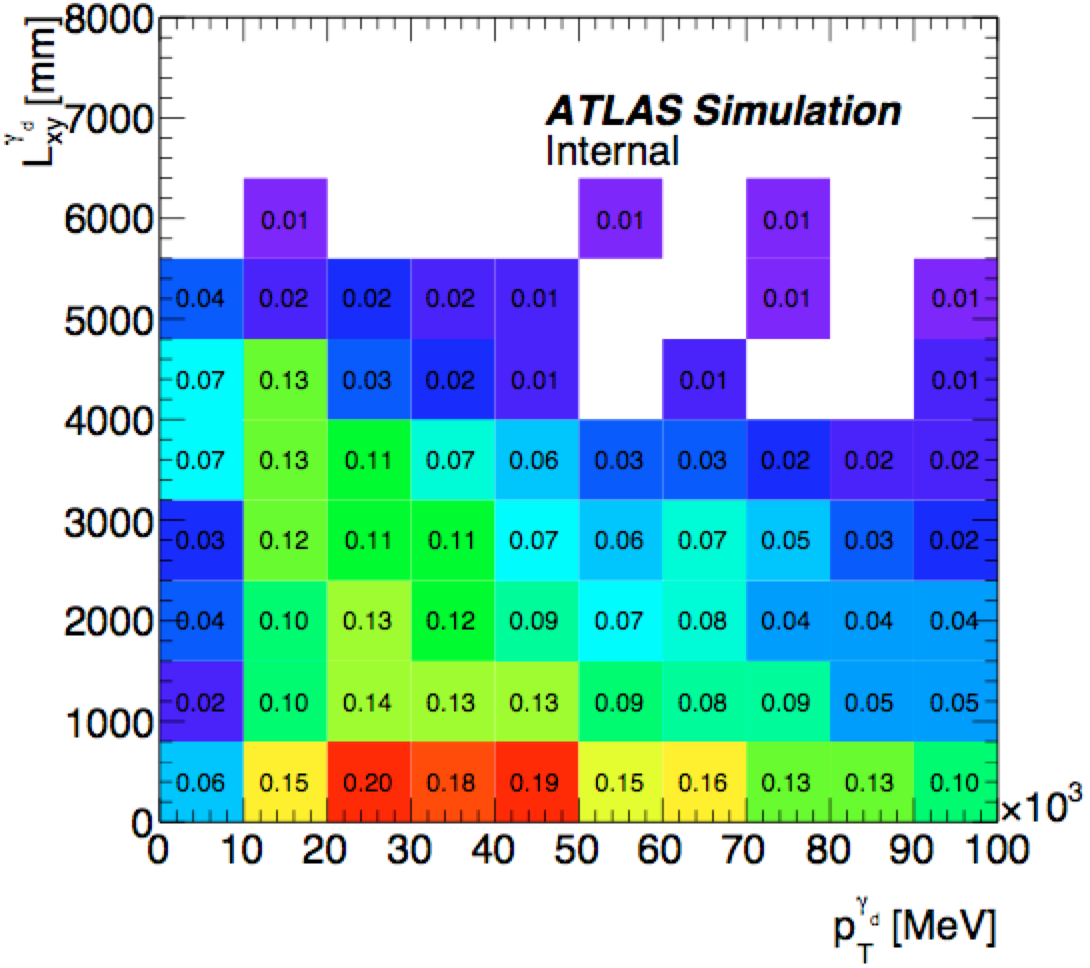
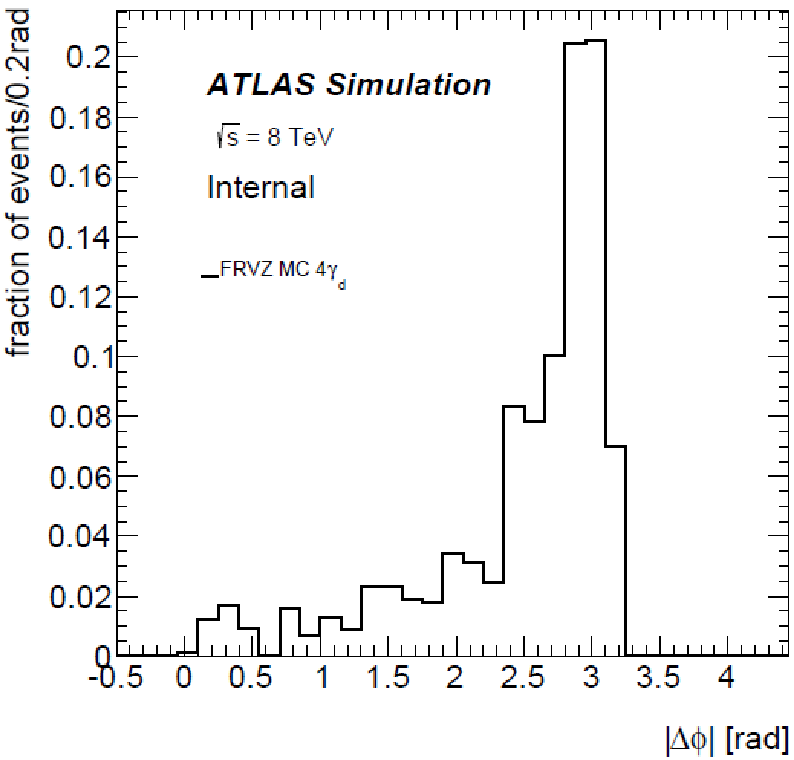
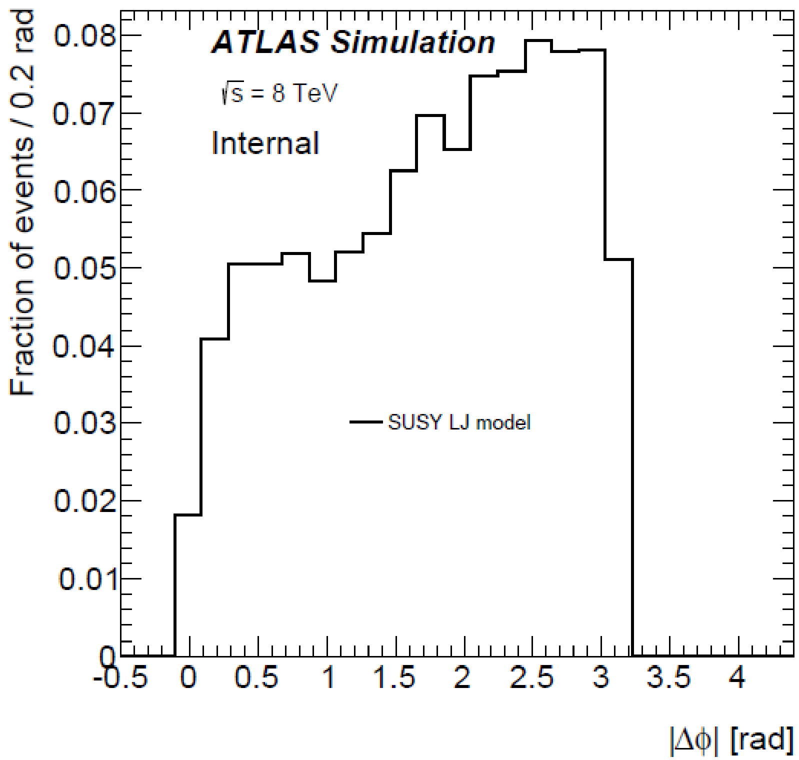


Figure 25: Reconstruction efficiency of LJ TYPE0 as a function of the γ_d decay point and of the p_T for single γ_d samples ($\gamma_d \to \mu\mu$) (barrel only).

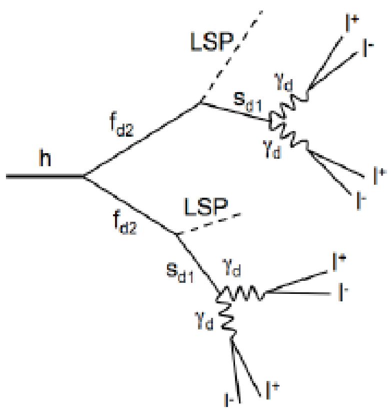
Additional cut at Event Level:
Angulare Aperture between the two LJ in the event -$\Delta\phi$-

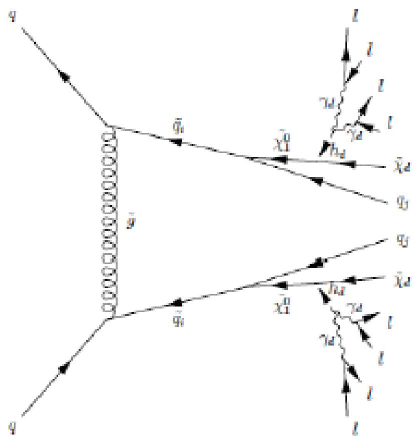




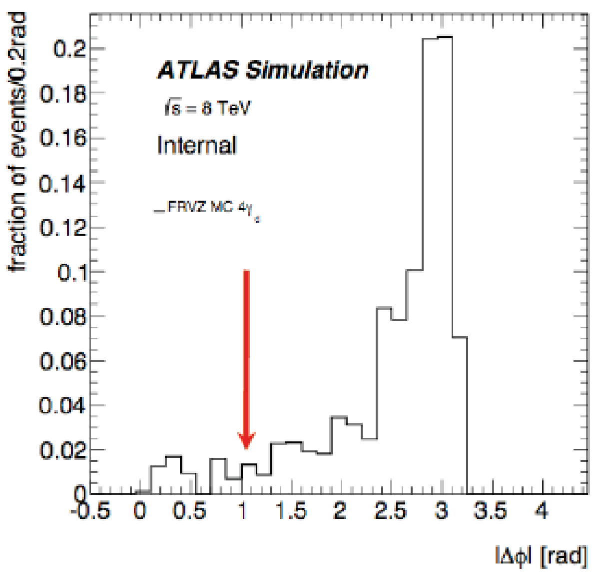
Δφ between the farthest LJ with respect to the leading p_T LJ in the event

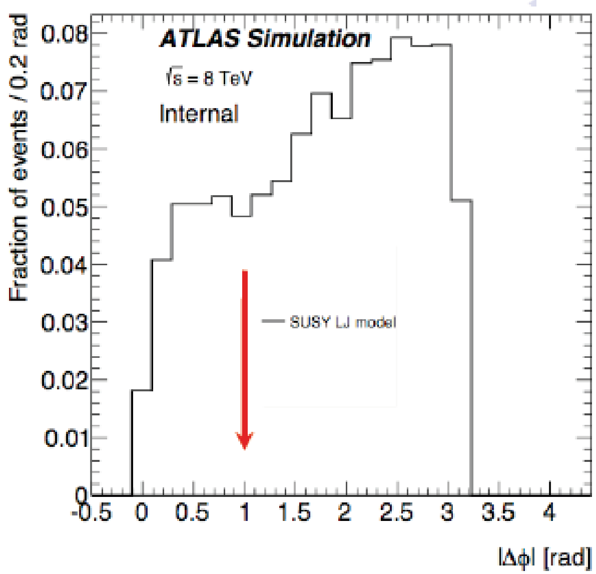
- Use dark photons from full simulation of Falkowsky-Ruderman-Volansky-Zumpan (FRVZ) model (see also later for details on such model) and SUSY LJ production

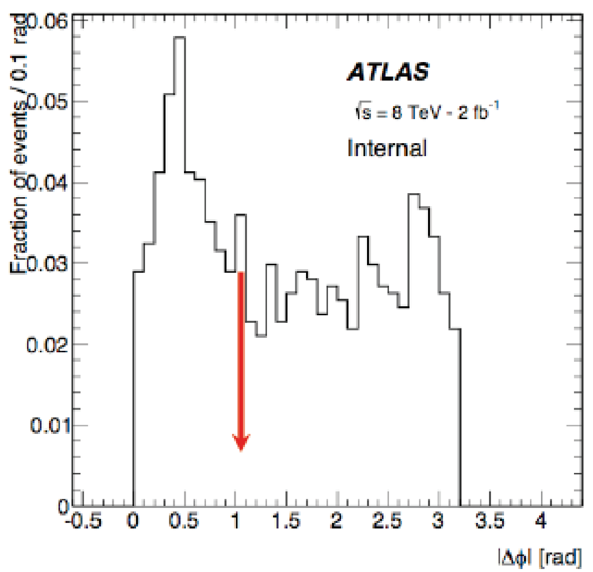




2fb^{-1} DATA







- |Δφ|>1 will reduce in a sensible way the background without strong losses for potential signals

SIGNIFICANCE

4.1 Selection criteria for LJ

In this section we describe the analysis cuts used for selecting LJs produced in the 2012 data collected by ATLAS. The main aim of the cuts is to extract the LJ signal from the overwhelming background of the standard p-p interactions. The main background source to the LJ signal is expected from QCD multi-jets production and from cosmic-ray muons crossing the detector in time coincidence with a bunch crossing interaction. Due to the lack of statistics available for the multi-jet low E_T Monte Carlo samples, events selected by single jet trigger (lowest available 15 and 35 GeV thresholds) in the first 2 fb^{-1} 2012 data have been used in order to study the discriminating variables that can be used to separate the signal from the QCD multi-jets background, reducing as much as possible the signal loss. Cuts for LJ selection have been optimized in order to maximize the signal significance defined as [27]

$$\sqrt{2((s+b)ln(1+s/b)-s)} \tag{1}$$

where s is the signal and b the background. For the LJ signal we have used the most unfavorable case, i.e. a LJ from an s_{d_1} of 10 GeV and a γ_d of 1500 MeV).
For the cosmic-ray background we have used a sample of events collected in the empty bunch crossings with the same triggers used to select our data sample (see Section 6).

Cut flow on Cosmics

cut	cosmic-ray background (number of events from triggers on empty bunches)
trigger selection	161951
good primary vertex	161951
LJ minimal request	11432
η cut for LJ TYPE2	7257
EM fraction cut for LJ TYPE2	7000
WIDTH cut for LJ TYPE2	4341
jet timing cut	80
no combined muons	80
ID isolation	80
$\Delta\phi$ cut	13

LJ pair type	Estimated cosmic-ray background $\Delta\phi \geq 1$
TYPE0 - TYPE0	15 ± 6 (*stat*)
TYPE0 - TYPE1	$0^{+2.3}_{-0}$ (*stat*)
TYPE0 - TYPE2	16 ± 7 (stat)
TYPE1 - TYPE1	$0^{+2.3}_{-0}$ (*stat*)
TYPE1 - TYPE2	$0^{+2.3}_{-0}$ (*stat*)
TYPE2 - TYPE2	2.9 ± 2.9 (*stat*)

Hidden Valley Models

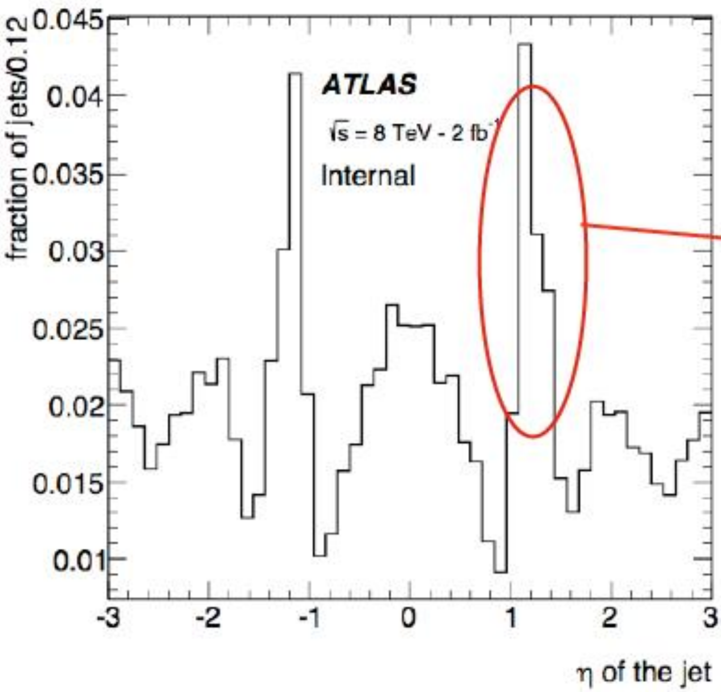
Higgs BR into the hidden sector = 10%, total luminosity = 20.34 fb^{-1}

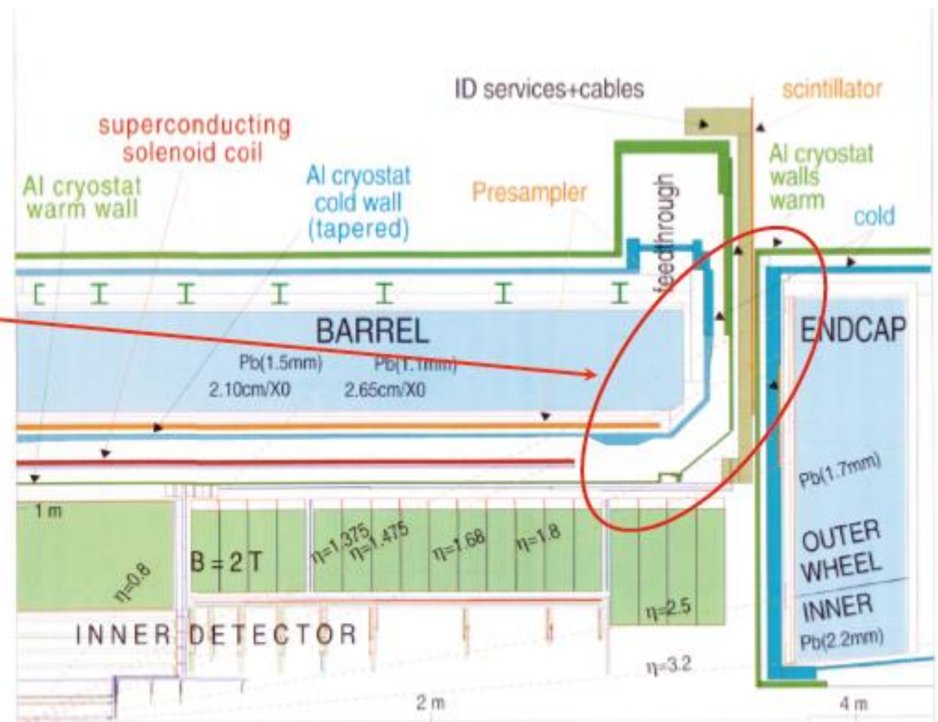
cut	4 γ_d FRVZ model (number of events in 20.34 fb^{-1})	2 γ_d FRVZ model (number of events in 20.34 fb^{-1})
trigger selection	2518	1330
good primary vertex	2516	1330
LJ minimal request	793	354
η cut for LJ TYPE2	350	165
EM fraction cut for LJ TYPE2	240	111
WIDTH cut for LJ TYPE2	240	111
jet timing cut	226	105
no combined muons	123	68
ID isolation	85	53
$\Delta\phi$ cut	84	50

LJ pair type	4 γ_d FRVZ model (number of events in 20.34 fb^{-1})	2 γ_d FRVZ model (number of events in 20.34 fb^{-1})
TYPE0 - TYPE0	31	20
TYPE0 - TYPE1	33	9
TYPE0 - TYPE2	3	10
TYPE1 - TYPE1	13	1
TYPE1 - TYPE2	4	2
TYPE2 - TYPE2	0	8

Jets in the transition regions and at high pseudorapidity

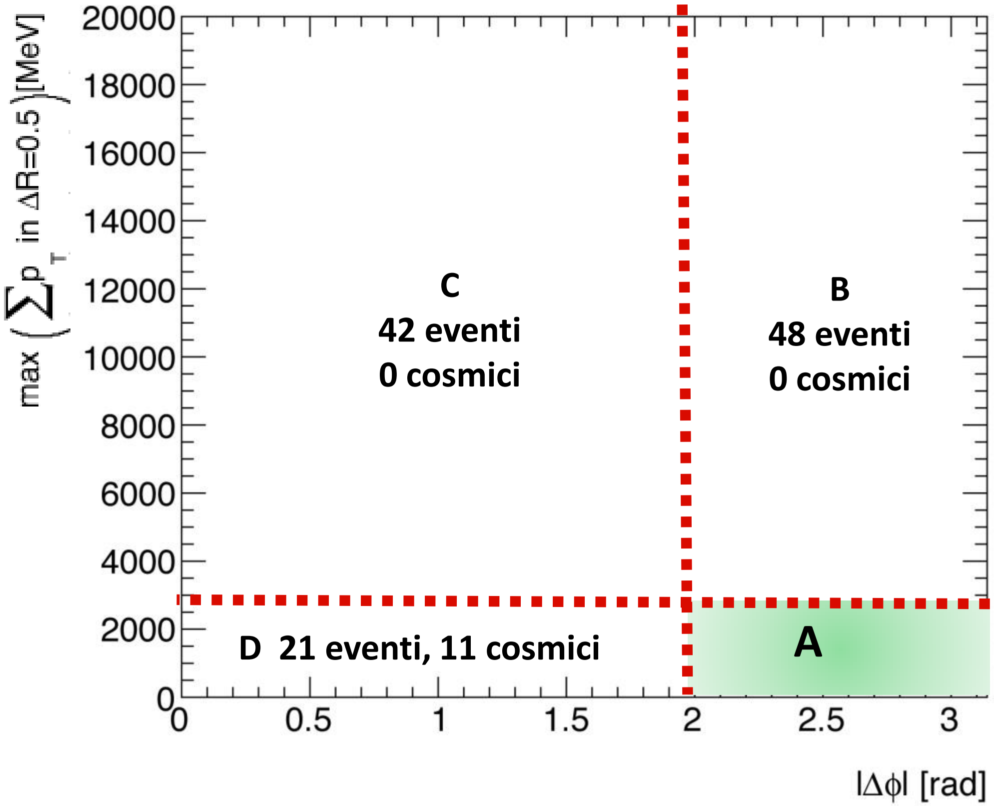
- Many jets mimic jets with low em fraction in the barrel-endcap transition regions and at high pseudorapidity
- remove jets with 1.0<|η|<1.5 and with em fraction > 0.1 from LJ TYPE 2 (as suggested from the egamma performance group)





QCD background evaluation: ABCD method

- QCD di-jet: MC statistics too low→ ABCD method
- Two variable ABCD method:
  background evaluation in the signal region (A) starting from the three control regions (BCD)
- Uncorrelated variables in this analysis: $\max \sum p_T$ e $|\Delta\phi|$



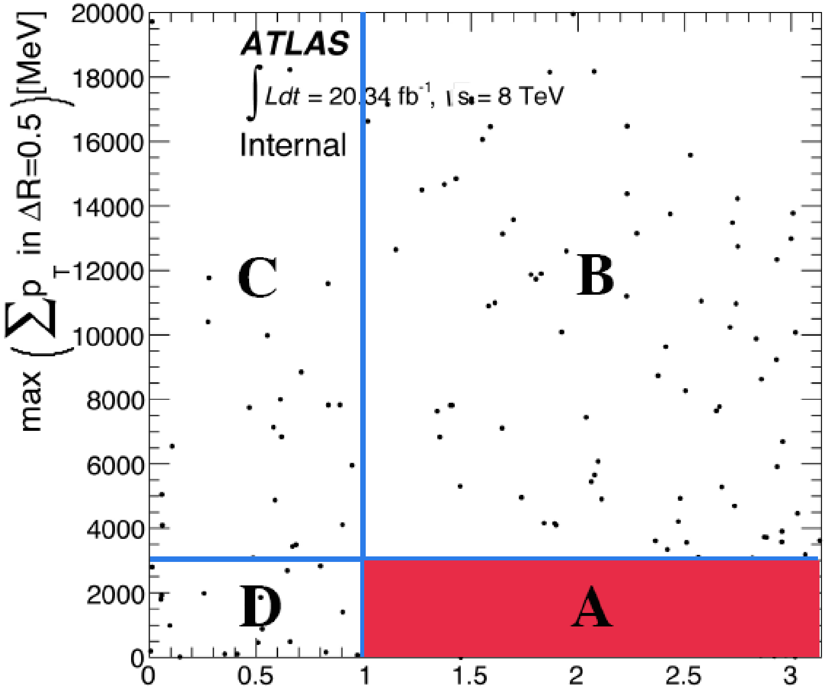
Signal Region:

$$\sum p_T < 3000 \text{ MeV AND } |\Delta\phi| > 2 \text{ rad}$$

$$\frac{N_A}{N_B} = \frac{N_D}{N_C} \rightarrow N_A = 48 * \frac{21}{42} = 24 \pm 7$$

Not only QCD di-jets, but also cosmics included

ABCD method



- **ABCD method background evaluation**
  The systematic uncertainties that can affect the background multi-jet estimation are related to the data-driven method used. The cuts used to define the various regions have been changes by 20% and the background values have been recomputed. This systematic uncertainty amounts to 15%.

  The effect of signal leakage will be taken into account using the latest simultaneous ABCD version suggest by the statistic forum (simultaneous fit of signal and background in the four regions), once the analysis will be unblinded.

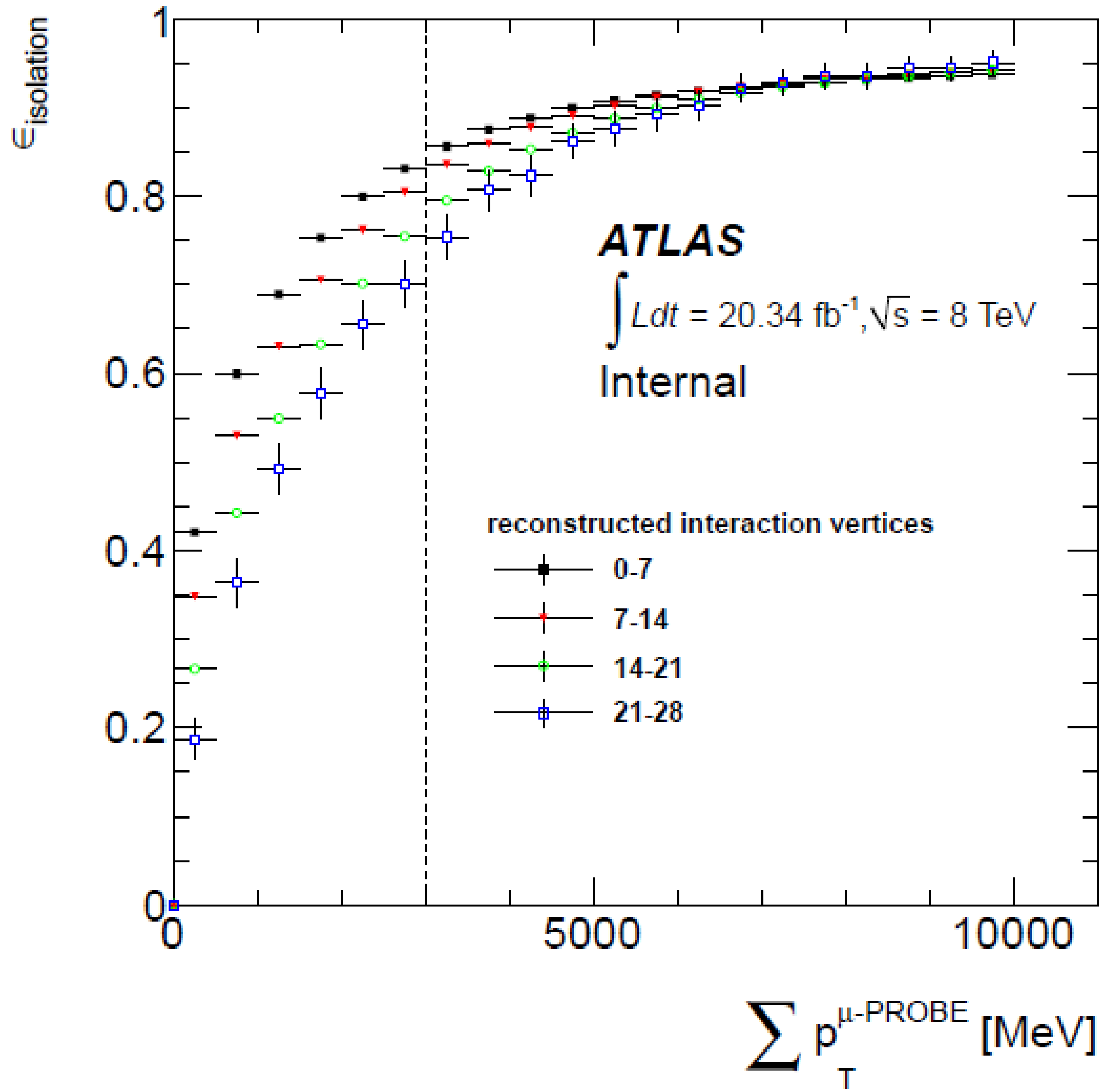
- All LJ pair TYPES

Data Type	Events in B	Events in C	Events in D	Expected Events in A
2012 COSMIC-RAY DATA	0	0	180 ± 23	34 ± 9
2012 DATA (cosmic rays subtracted)	696 ± 26	484 ± 22	59 ±27	85± 30

- Removing TYPE2-TYPE2 pairs: QCD background is expected to give the maximum contribution; depending on the type of model, TYPE2 - TYPE2 events can be removed or not, depending on the ratio expected-signal to background

Data Type	Events in B	Events in C	Events in D	Expected Events in A
2012 COSMIC-RAY DATA	0	0	2.9±2.9	32 ± 9
2012 DATA (cosmic rays subtracted)	78 ±9	22 ±5	16 ± 4	57 ±22

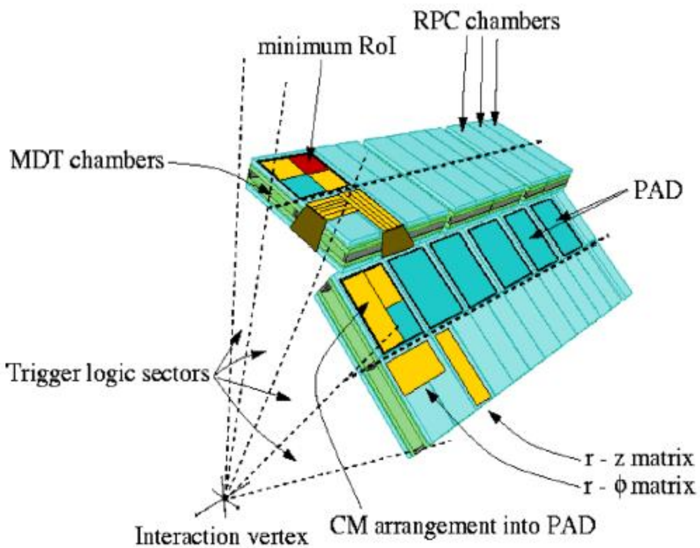
Effect of the pile-up on the isolation in ID

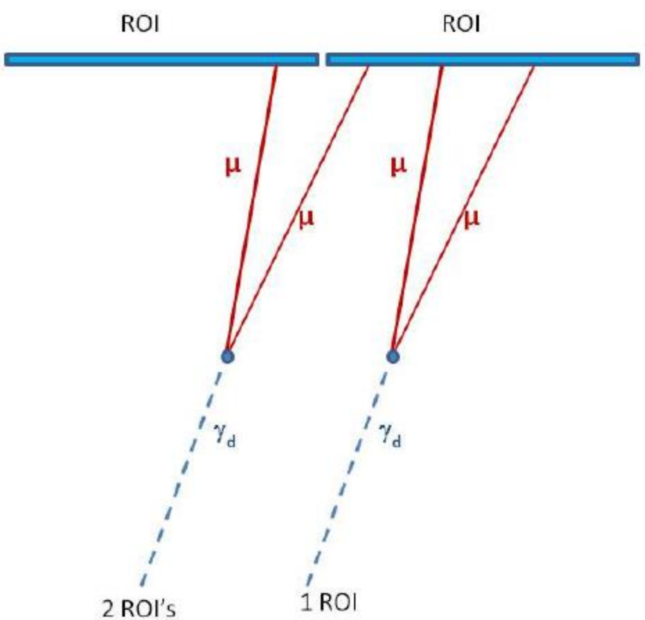


Trigger Efficiency

A large fraction of the standard ATLAS triggers are strictly linked to the primary vertex and therefore are very inefficient in selecting displaced decay vertices. Therefore we have used dedicated triggers like the Hidden Valley (HV) triggers [28, 29] and triggers that are not linked to the primary vertex position. In order to search for LJs TYPE0 and TYPE1 we need a multi-muon trigger that does not require combined MS-ID muon tracks, that has a relatively low p_{T} threshold and is unprescaled over the full 2012 data taking period.

Available single muon triggers and di-muon triggers with displaced vertex cannot be used because they are prescaled or with too high p_{T} threshold. The only available HLT triggers satisfying our requirements is the EF_3mu6_MSonly that starts from a three L1 muons with a $p_T \geq 6$ GeV, reconstructed only in the MS. A single jet trigger could be used to select LJs TYPE1, but the available low threshold jet triggers (e.g. 15, 35 or 80 GeV) were strongly prescaled in 2012 data taking. The higher threshold jet trigger are useless, as ther LJ signal can very well be below the 80 GeV. For LJs TYPE2 the only unprescaled available trigger is one of the HV triggers, the $EF\_j35\_a4tcem\_L1TAU\_LOF\_HV$ that is seeded by a tau40 L1 and requires a very low em fraction for the jet [29].

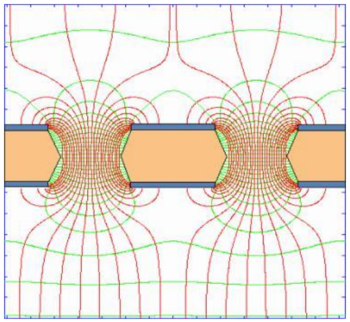




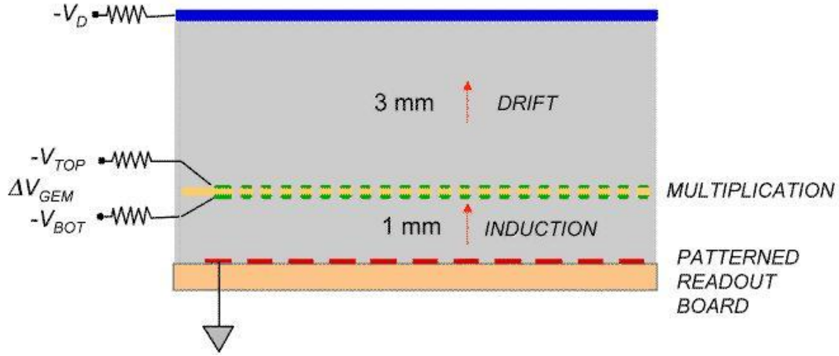
Gas Electron Multiplier

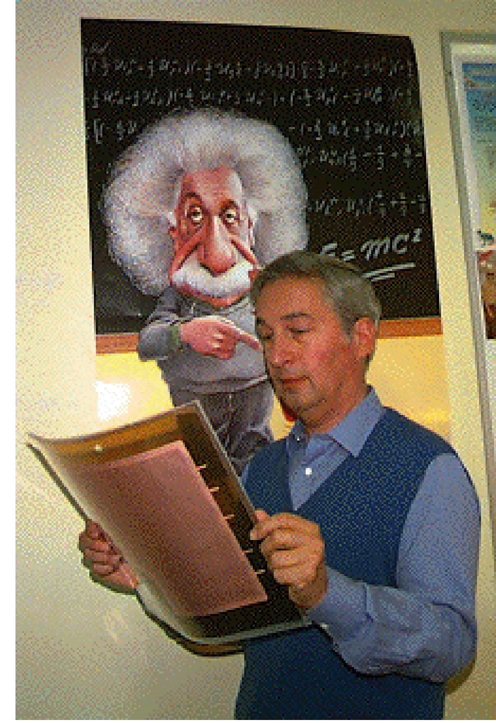
Initially developed as a preamplifier stage for an MSGC, the **G**as **E**lectron **M**ultiplier (**GEM**) became soon a detector on its own.

E field



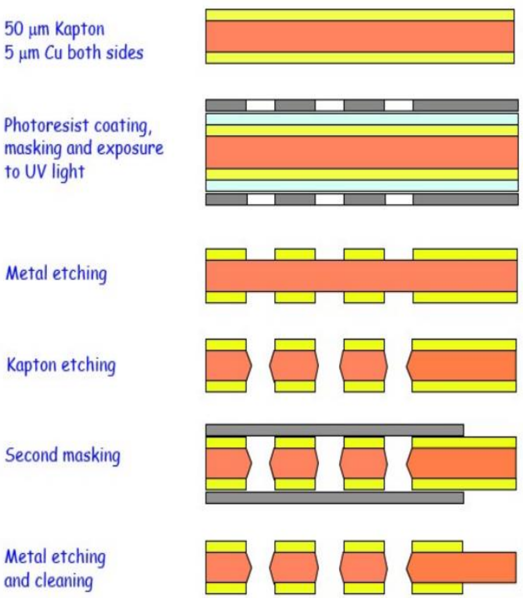
Structure

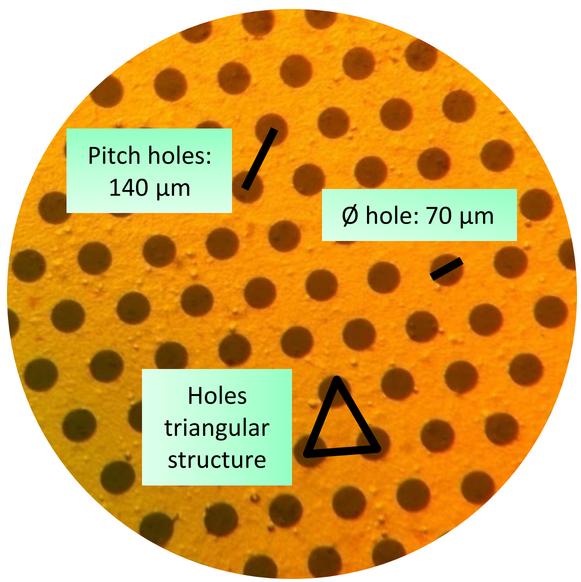




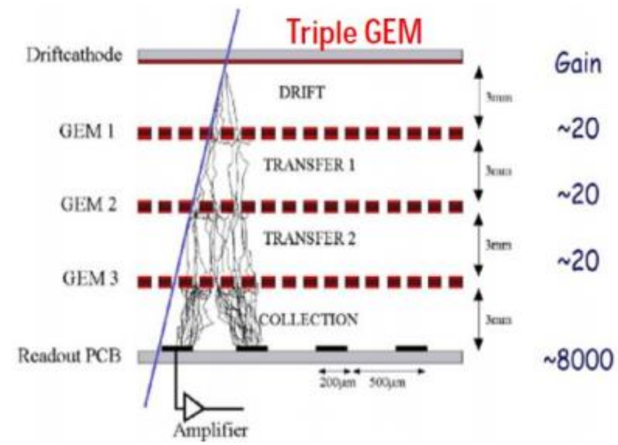
(1999, F.Sauli)

Production steps



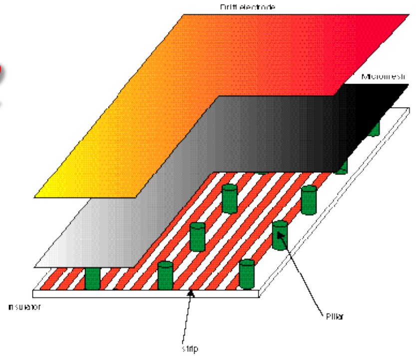


Improved GEM



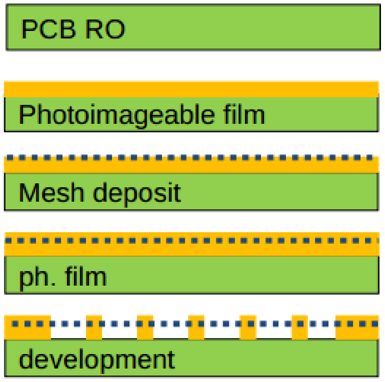
Spread of the avalanche over many active holes → reduction of spark probability

MicroMesh Gaseous Structure

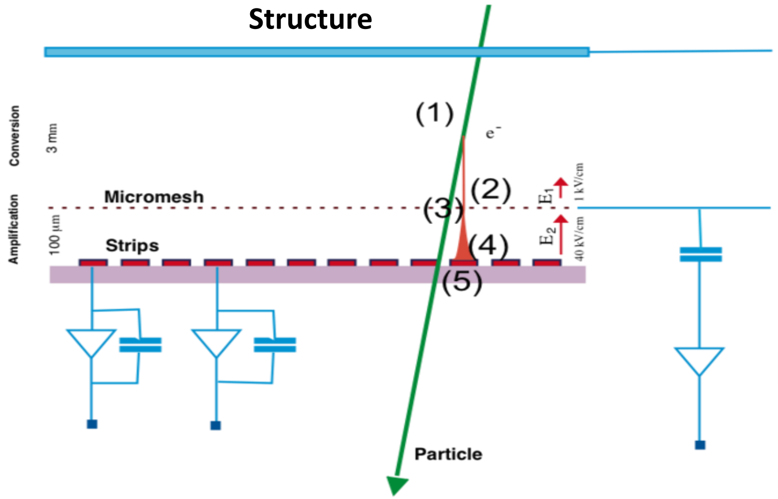


Parallel plate chamber where the amplification takes place in a thin gap, separated from the conversion region by a fine metallic mesh.

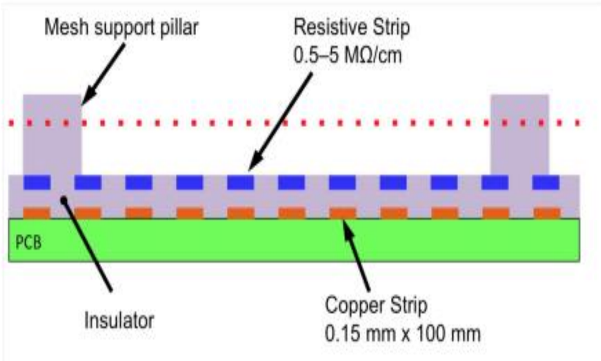
Production steps



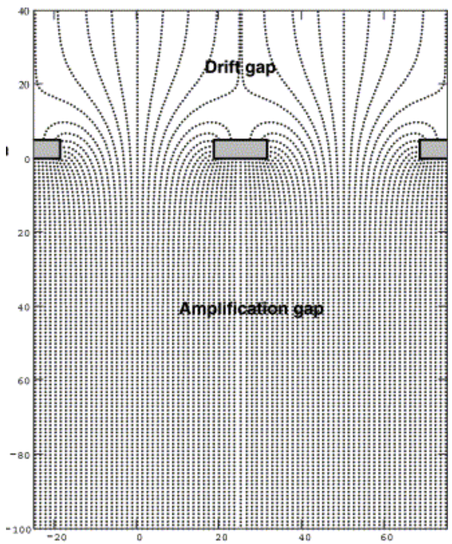
Structure

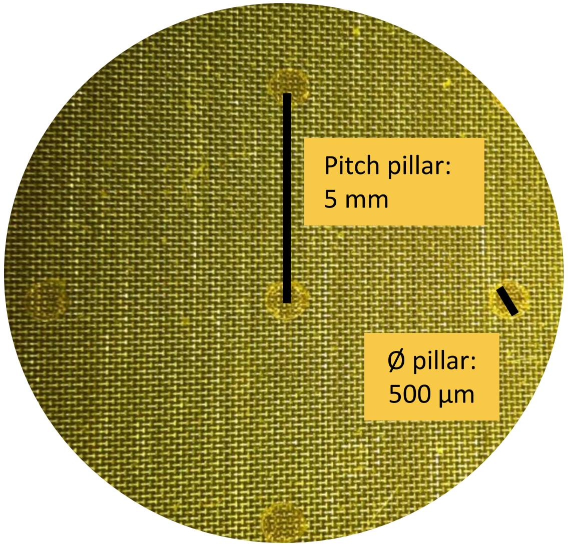


Improved MM



E field





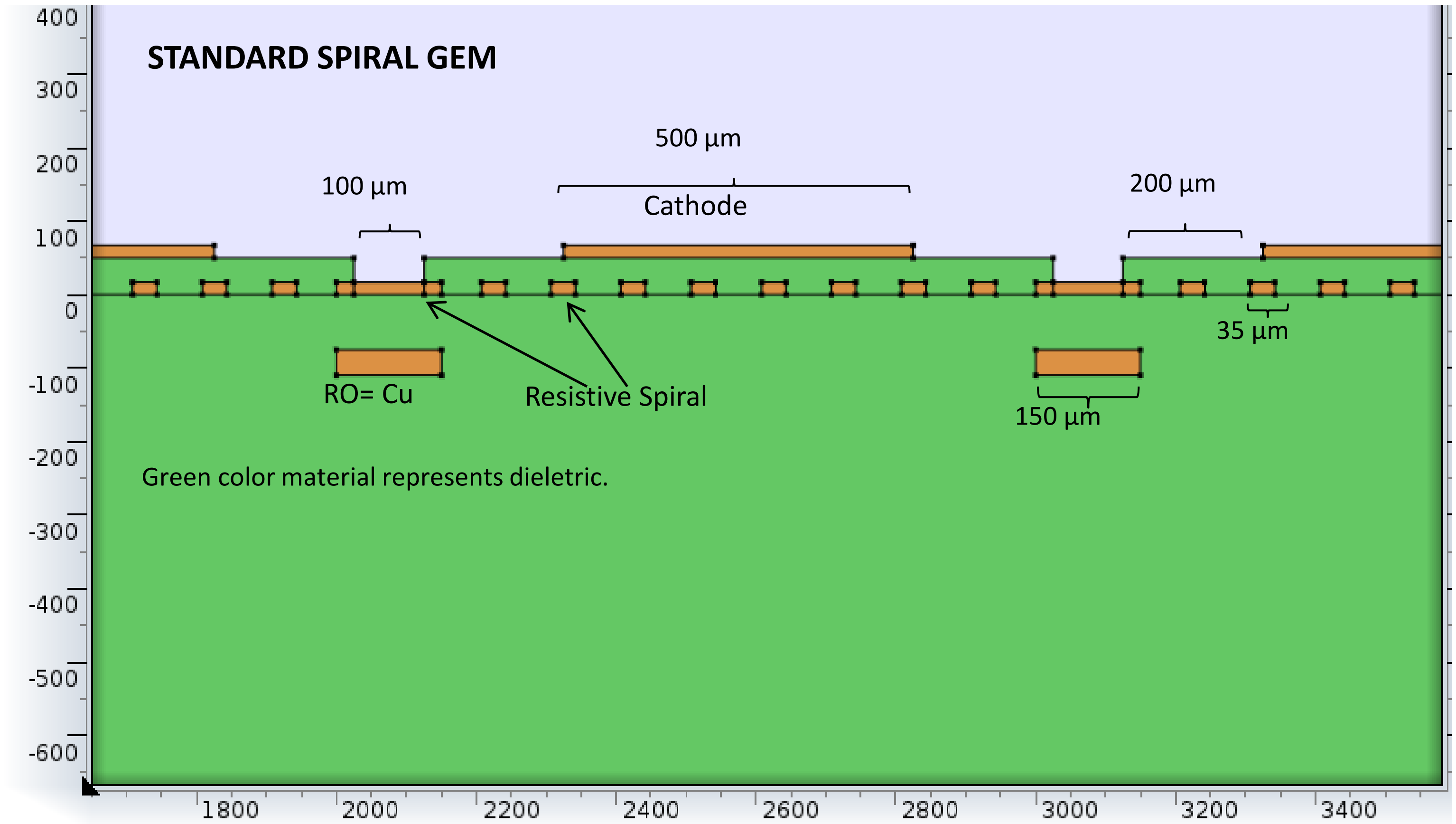
Resistive material:

not reduction of sparks but limit their impact on performance of the detector (HV drops become insignificant).

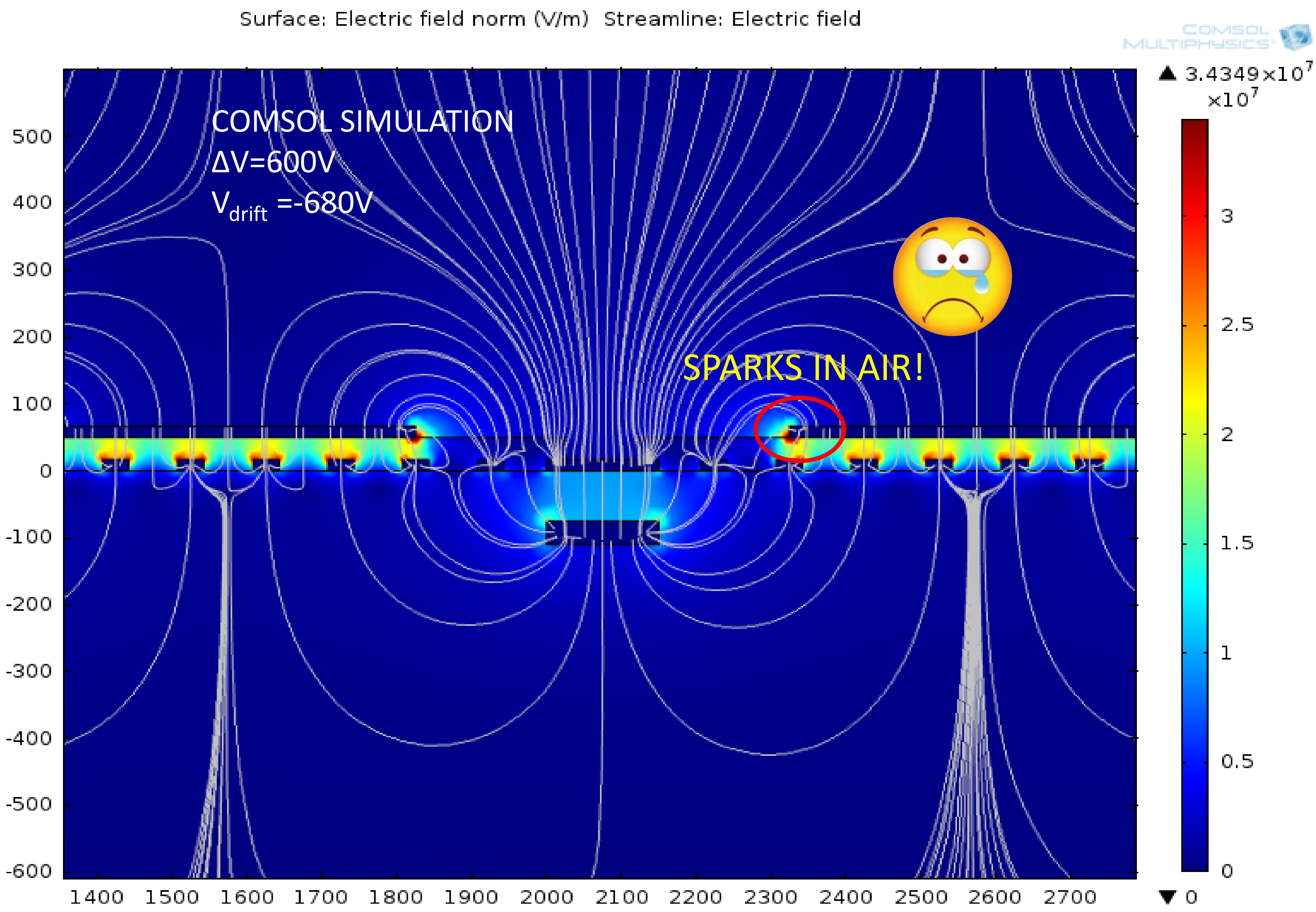
Strips instead of layer:

to avoid charge spreading and keep are affected by discharges as small as possible.

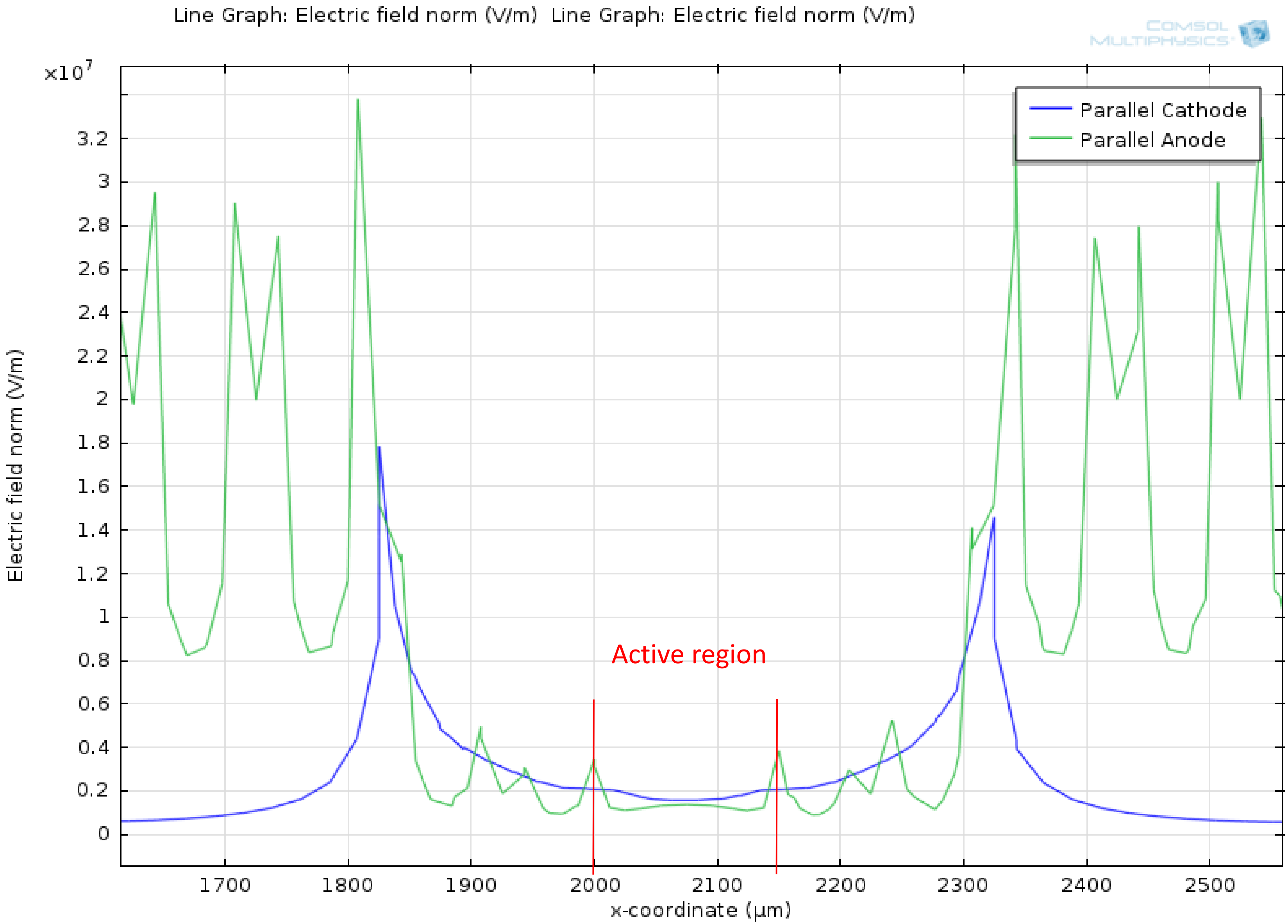
Spiral Detector



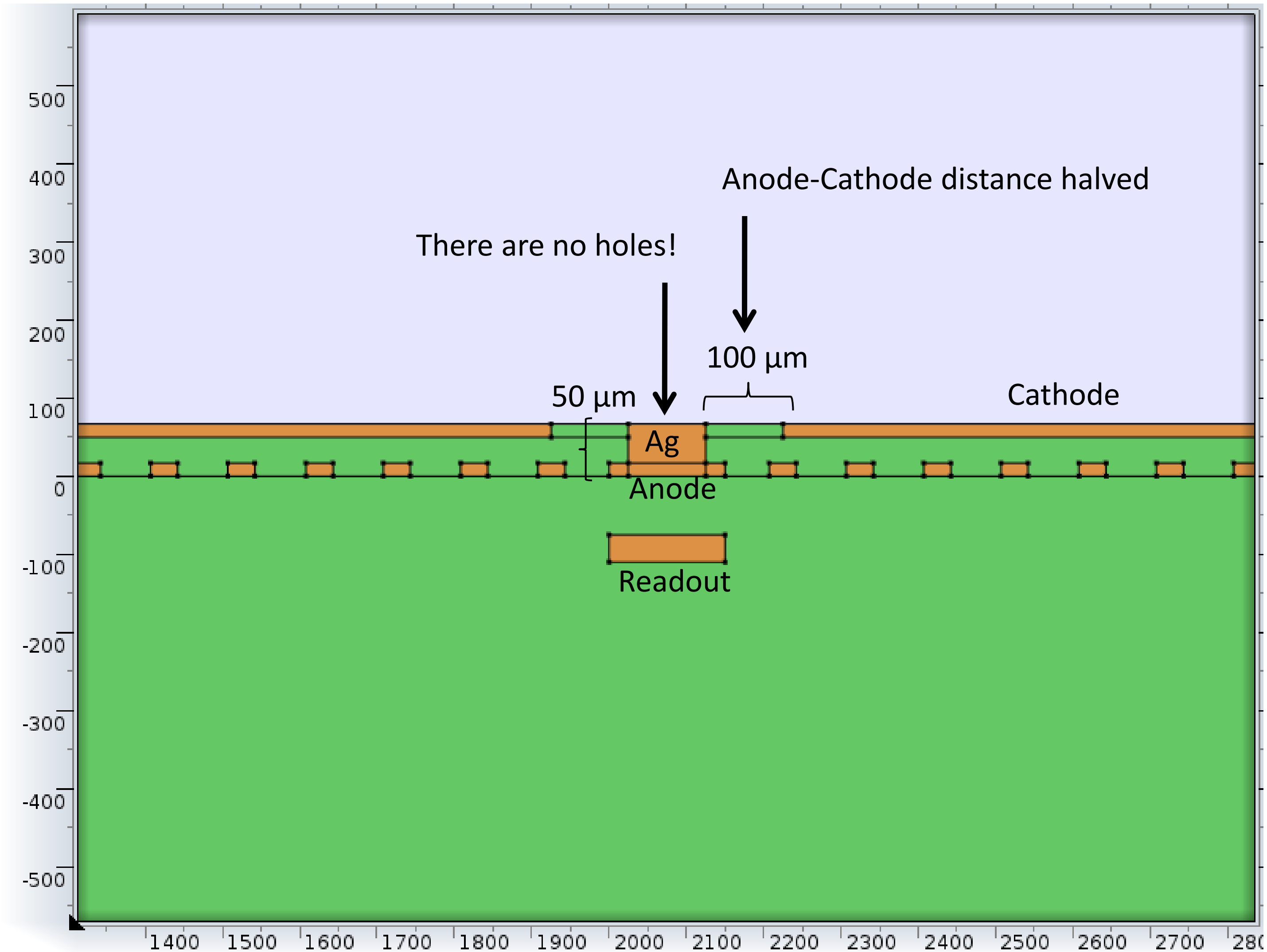
Spiral Detector



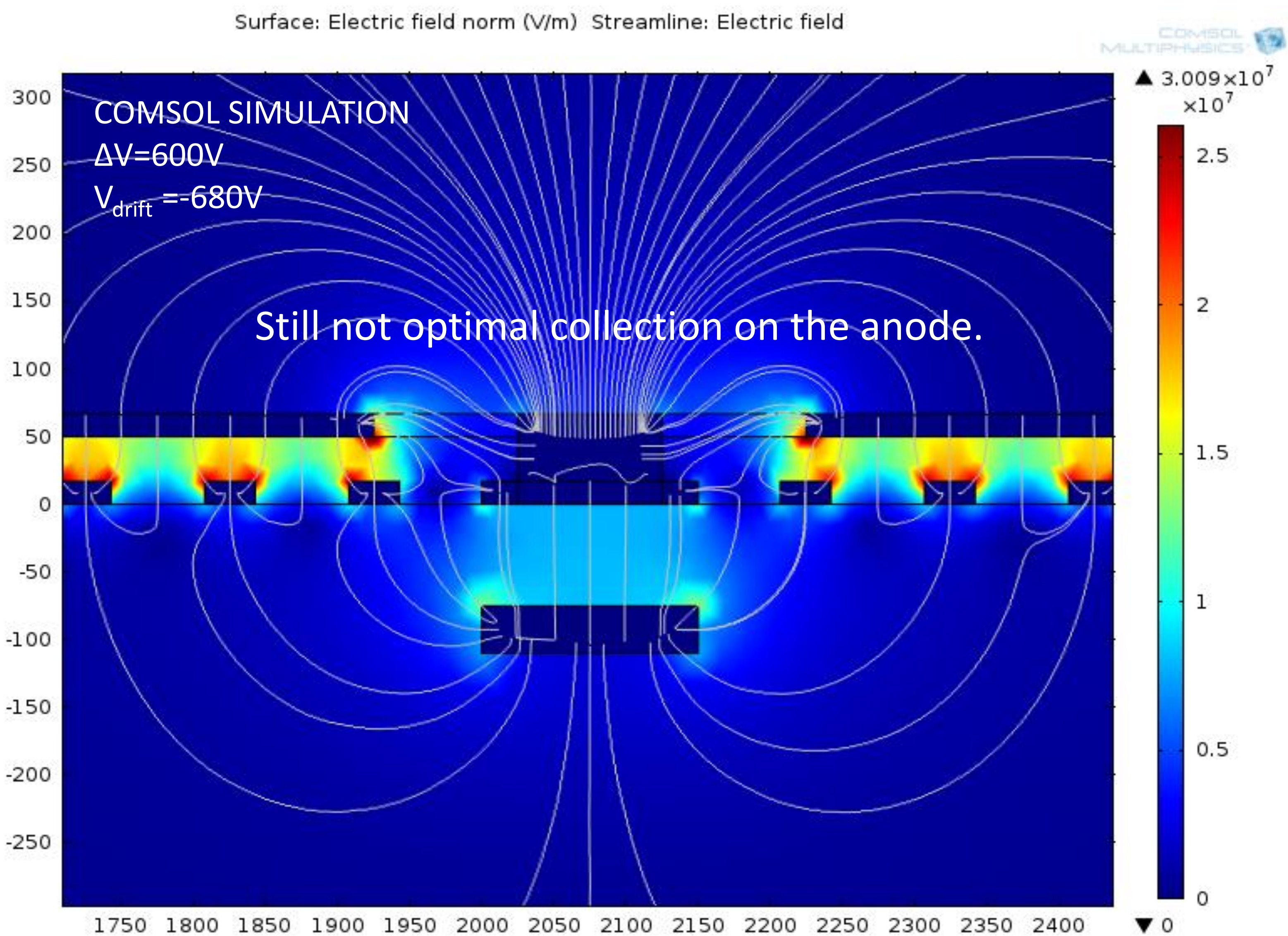
Spiral Detector



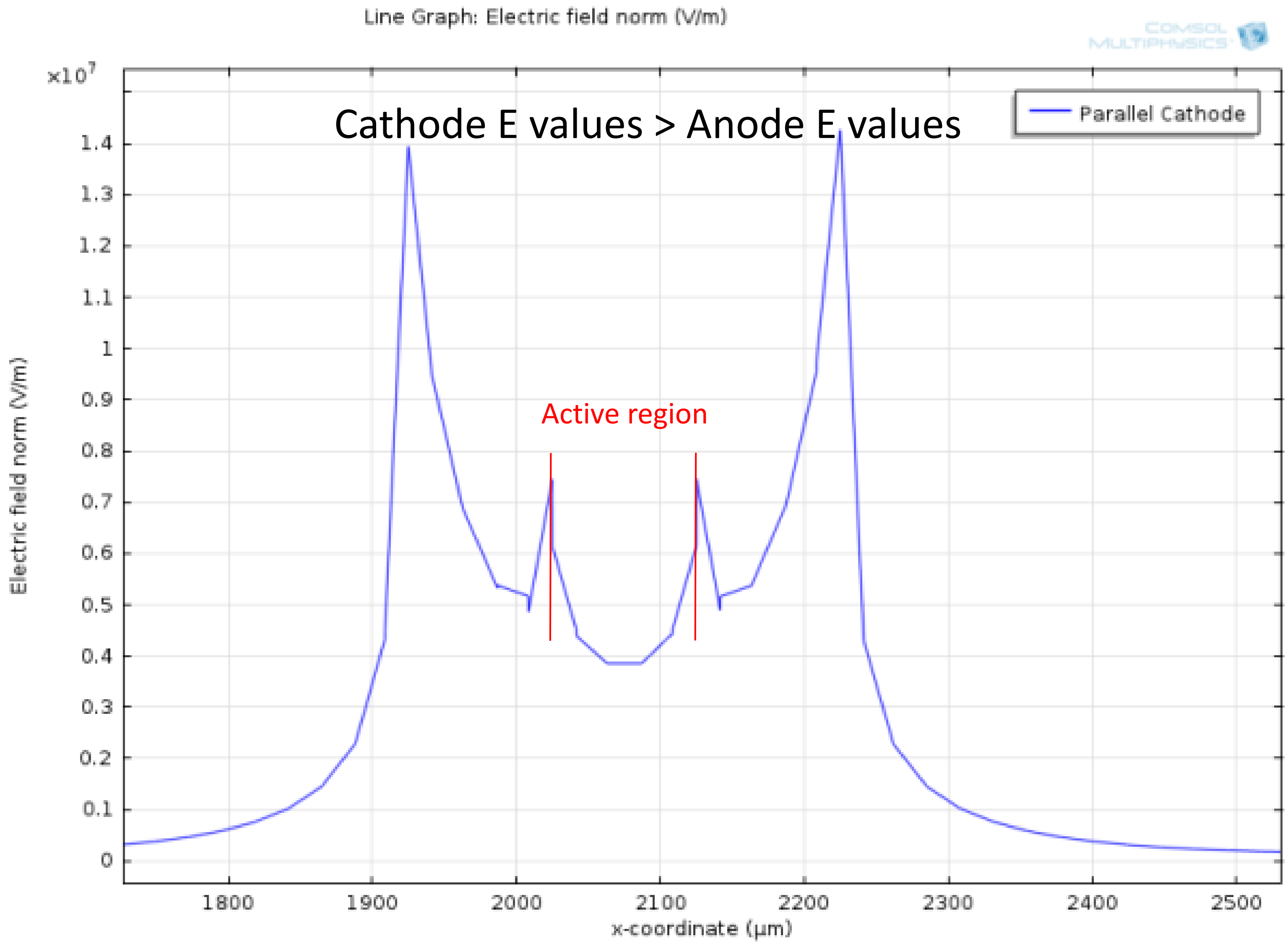
Spiral Detector –First Improvement-



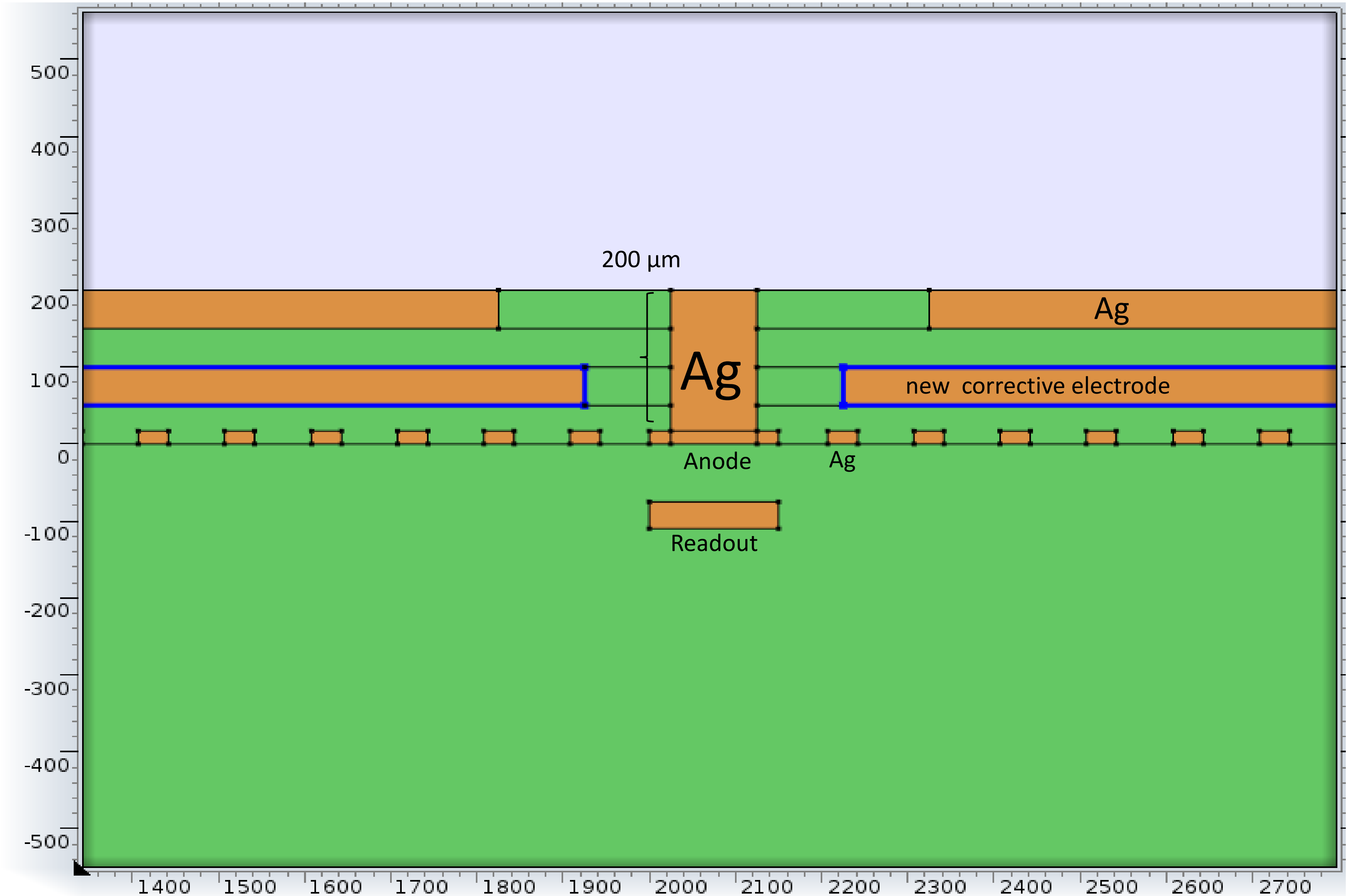
Spiral Detector –First Improvement-



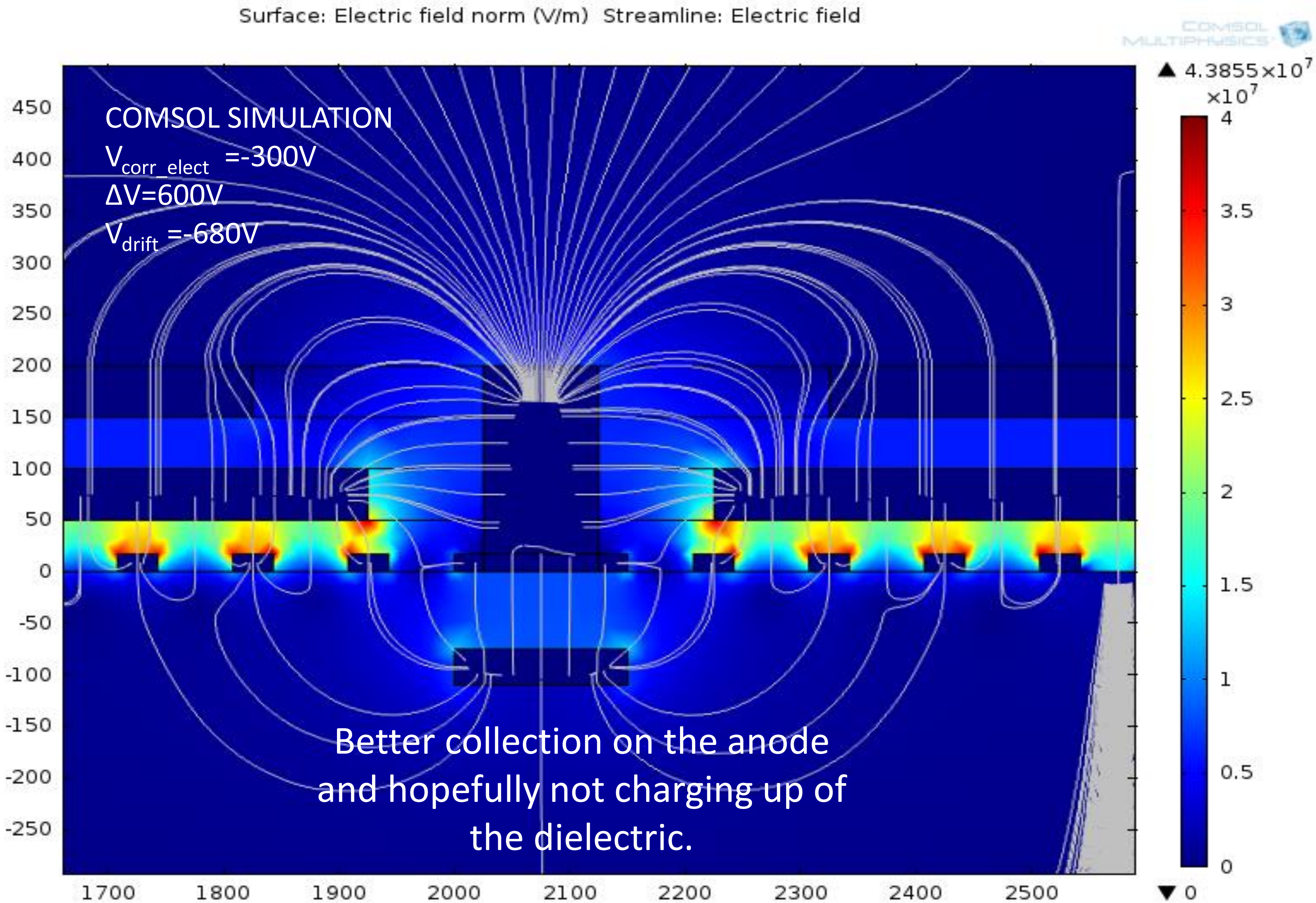
Spiral Detector –First Improvement-



Spiral Detector –Second Improvement-



Spiral Detector –Second Improvement-



Spiral Detector –Second Improvement-