ATLAS results relevant to Astroparticle Physics

Luminosity calibration, minimum-bias measurements, searches for dark matter, connection to IACTs

David Berge, DESY and Humboldt University Berlin

31. October 2018, ISAPP 2018

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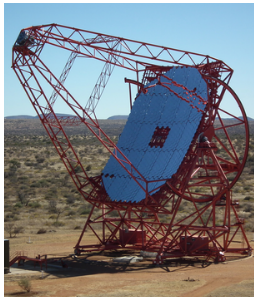
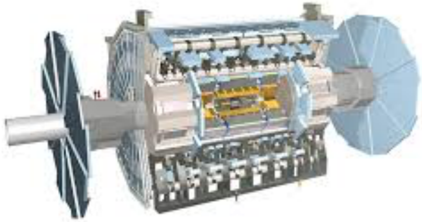
H.E.S.S.

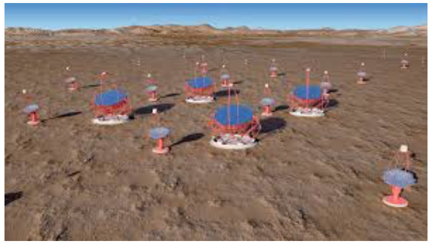


ATLAS EXPERIMENT



cta cherenkov telescope array

the observatory for ground-based gamma-ray astronomy



HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Collider physics

$$\dot{R} = L \cdot \sigma \quad \Longleftrightarrow \quad \sigma = \frac{\dot{R}}{L}$$

- The luminosity of a collider controls the number of produced events per unit time; the higher, the better!

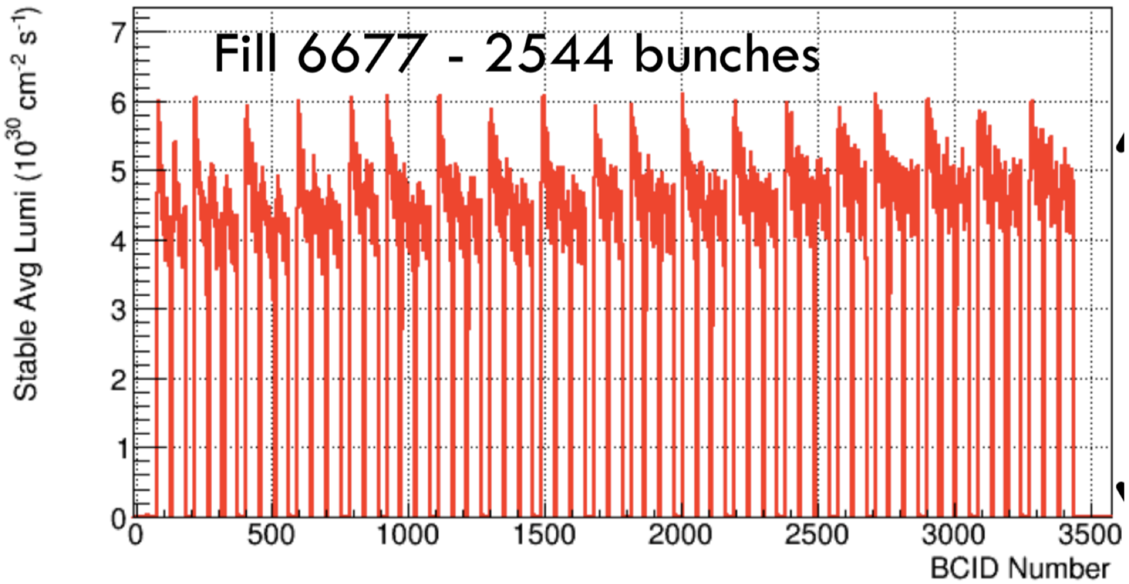
Collider physics

$$\underset{s^{-1}}{\dot{R}} = \underset{cm^{-2}s^{-1}}{L} \cdot \underset{\substack{cm^{2} \\ \downarrow}}{\sigma} \iff \sigma = \frac{\dot{R}}{L}$$

$$(\text{barn: } 1b = 10^{-24} cm^{2})$$

- The luminosity of a collider controls the number of produced events per unit time; the higher, the better!

Collider physics



ATLAS bunch-by-bunch lumi,
S.Valentinetti, LHCP2018

- The luminosity of a collider controls the number of produced events per unit time; the higher, the better!
- Needed bunch-by-bunch to correct pile-up effects on physics measurements

Luminosity measurements

How bright are we?

$$L = \frac{\dot{R}}{\sigma}$$

measure

calculate or measure

- Either measure a process with predictable cross section
    - e+e- scattering at lepton collider
    - Elastic scattering, related to cross section via optical theorem, see Monday‘s lecture by R.Engel
- Or measure cross section in special calibration runs

Luminosity measurements

How bright are we?

$$\mathcal{L} = \frac{\dot{R}}{\sigma} = \frac{\varepsilon \cdot \dot{R}}{\underset{\substack{\uparrow \\ \text{detector} \\ \text{efficiency}}}{\varepsilon} \cdot \sigma} = \frac{\dot{R}_{\text{visible}}}{\sigma_{\text{visible}}}$$

Luminosity measurements

How bright are we?

measure

$$L = \frac{\dot{R}}{\sigma} = \frac{\varepsilon \cdot \dot{R}}{\varepsilon \cdot \sigma} = \frac{\dot{R}_{\text{visible}}}{\sigma_{\text{visible}}}$$

detector efficiency

determine

measure following Simon van der Meer,

"van der Meer" scans

Luminosity measurements

How bright are we?

measure

$$L = \frac{\dot{R}}{\sigma} = \frac{\varepsilon \cdot \dot{R}}{\varepsilon \cdot \sigma} = \frac{\dot{R}_{\text{visible}}}{\sigma_{\text{visible}}}$$

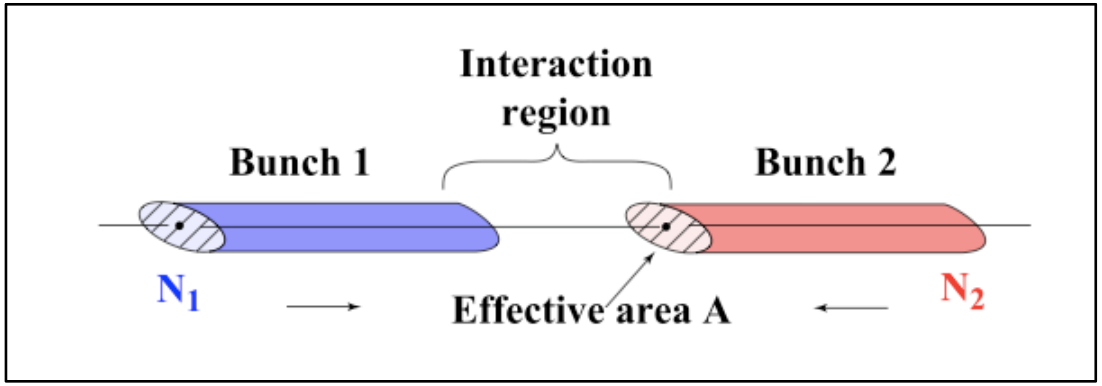
measure following Simon van der Meer, "van der Meer" scans

detector efficiency

determine

- Calibrate the event rate seen by any(!) detector to the corresponding luminosity once, in a special LHC beam scan
- Use to determine the luminosity in any(!) physics fill from there on

Luminosity from beam parameters



For Gaussian bunches:

$$\mathcal{L} = \frac{N_1 N_2 n_b f_{LHC}}{4 \pi \sigma_x \sigma_y}$$

For generic bunch densities

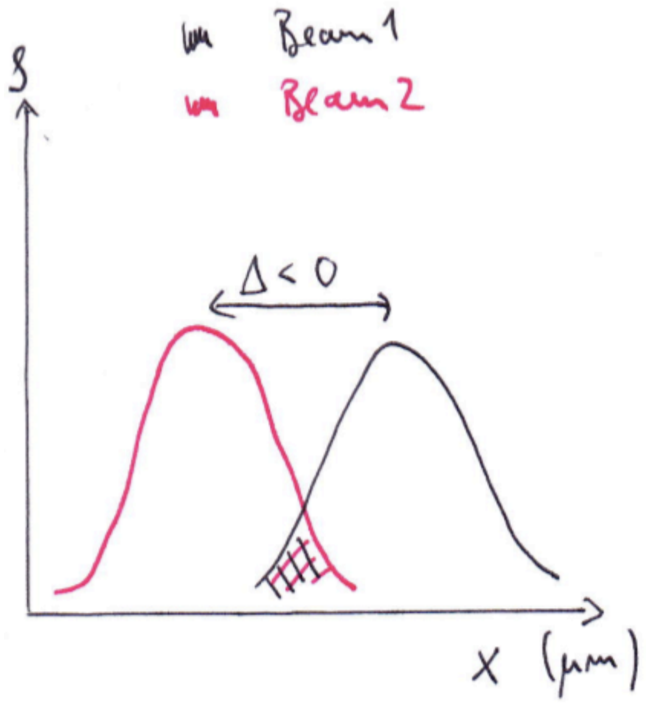
$$\mathcal{L} = 2 N_1 N_2 n_b f_{LHC} \int \rho_1(x,y)\, \rho_2(x,y)\, dx\, dy$$

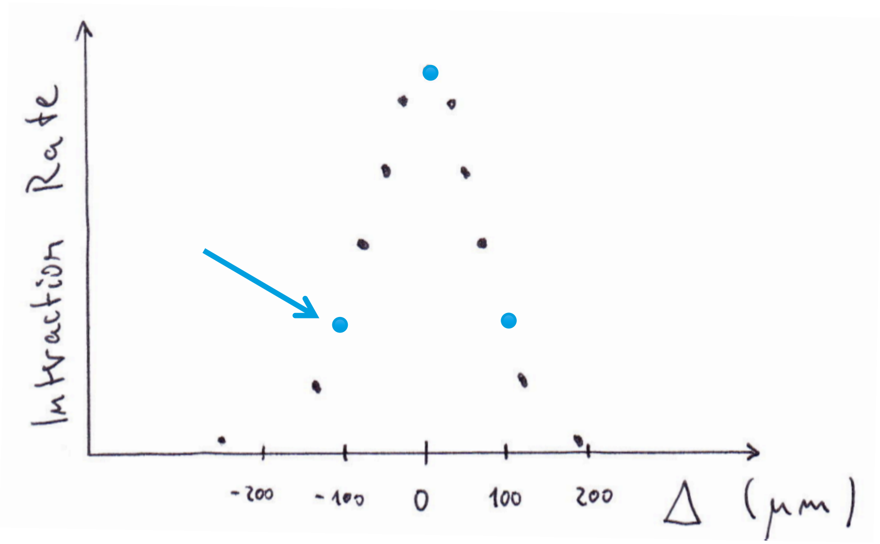
Problem: difficult to measure σ_x and σ_y (or ρ_x and ρ_y) precisely

Solution: van der Meer separation scans…

Luminosity calibration at colliders

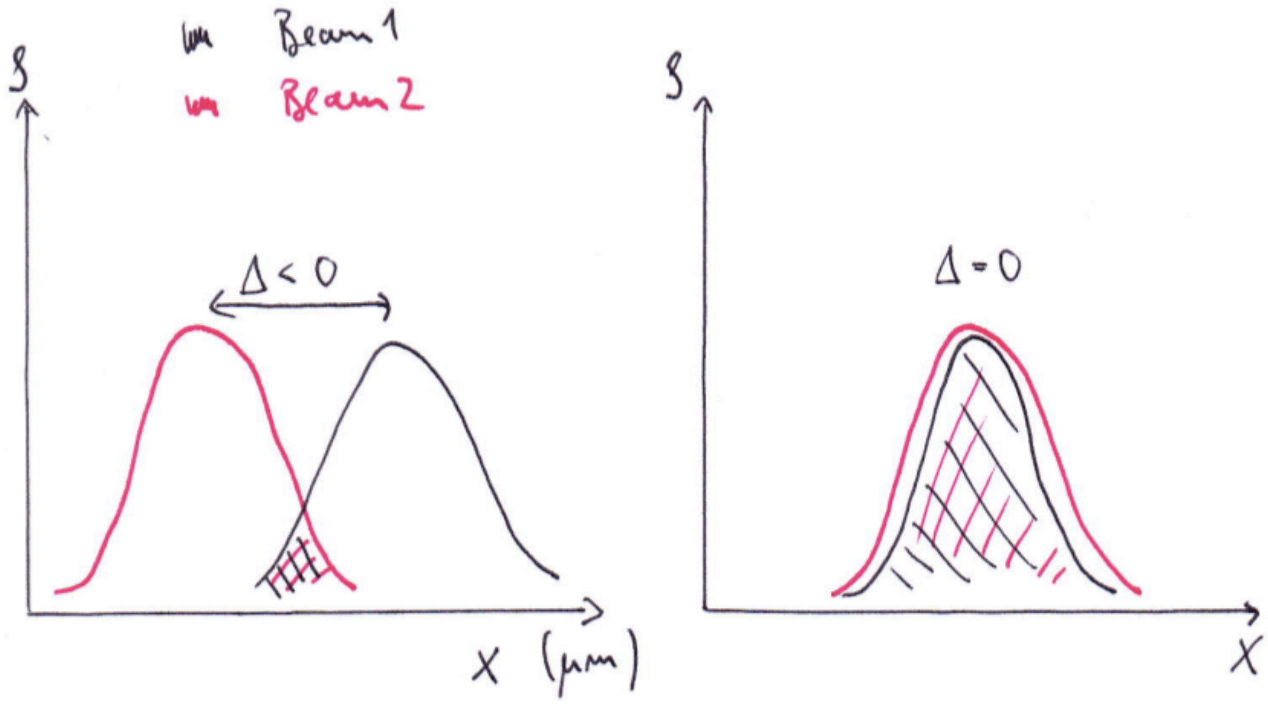
van der Meer scans

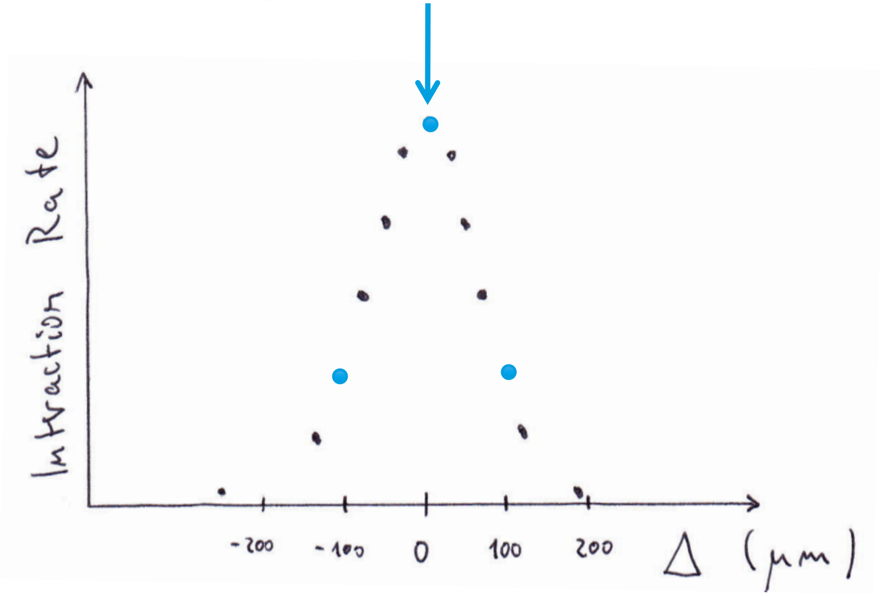




Luminosity calibration at colliders

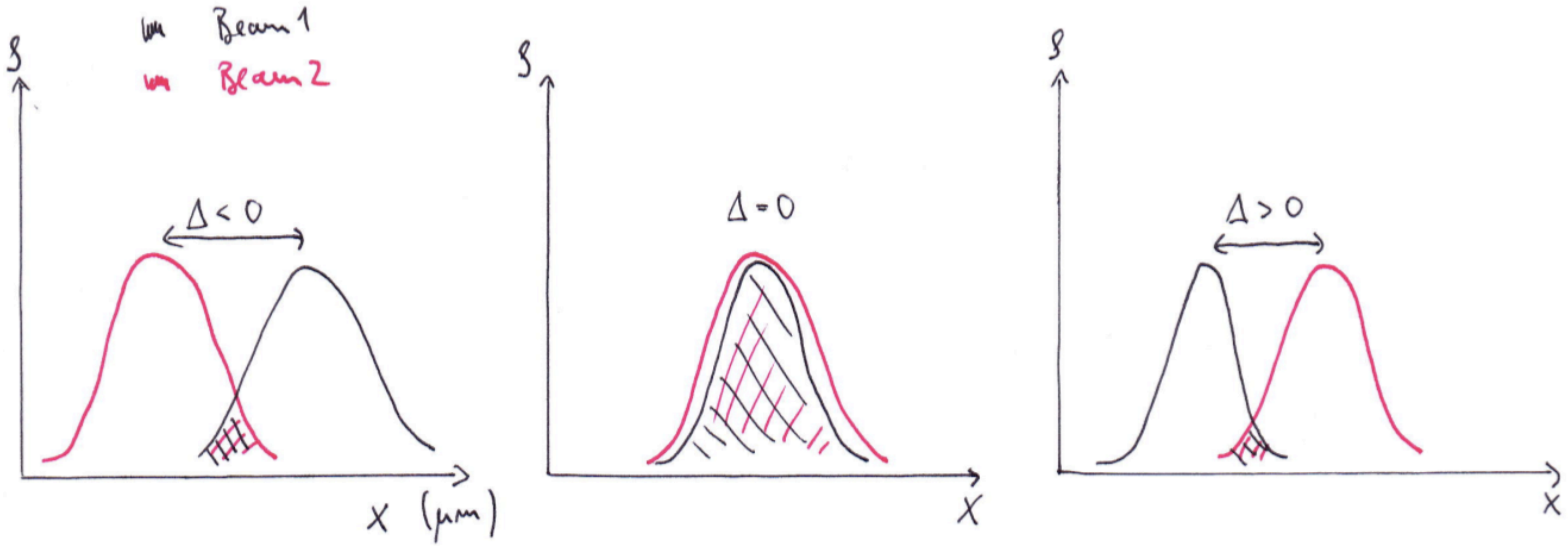
van der Meer scans

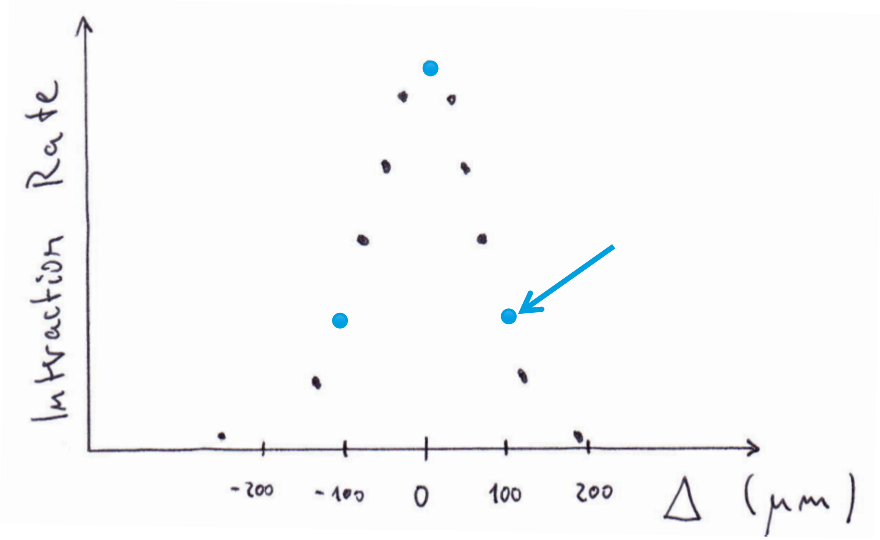




Luminosity calibration at colliders

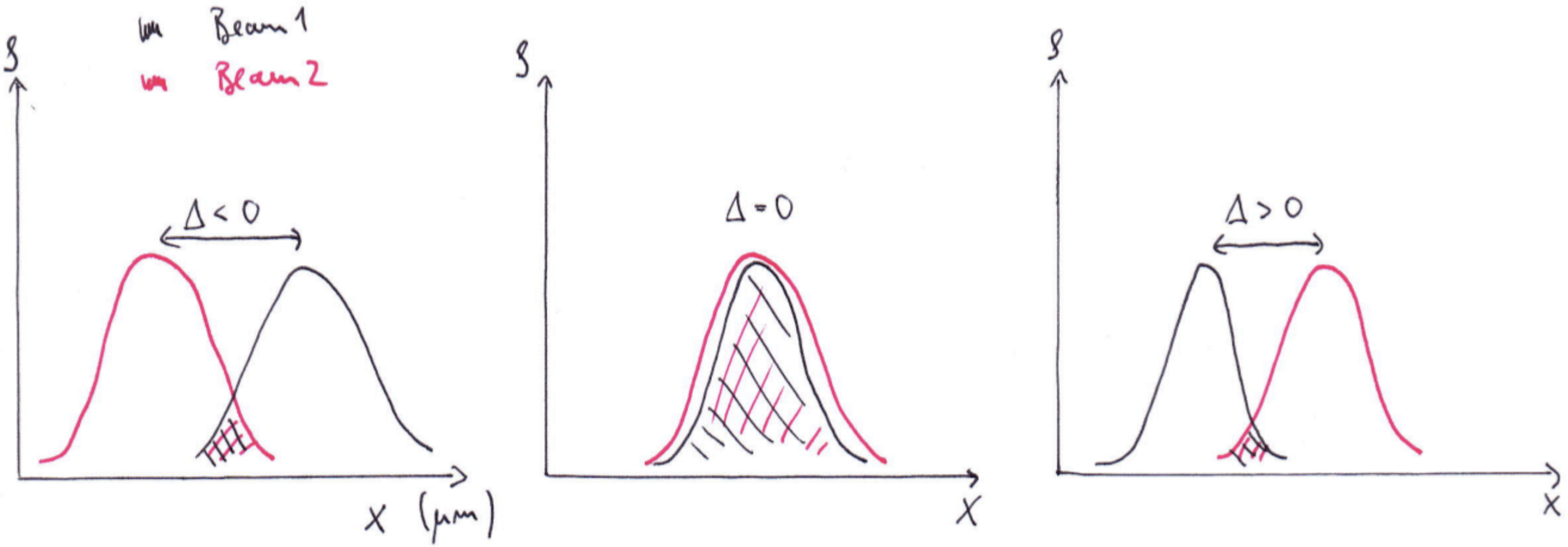
van der Meer scans

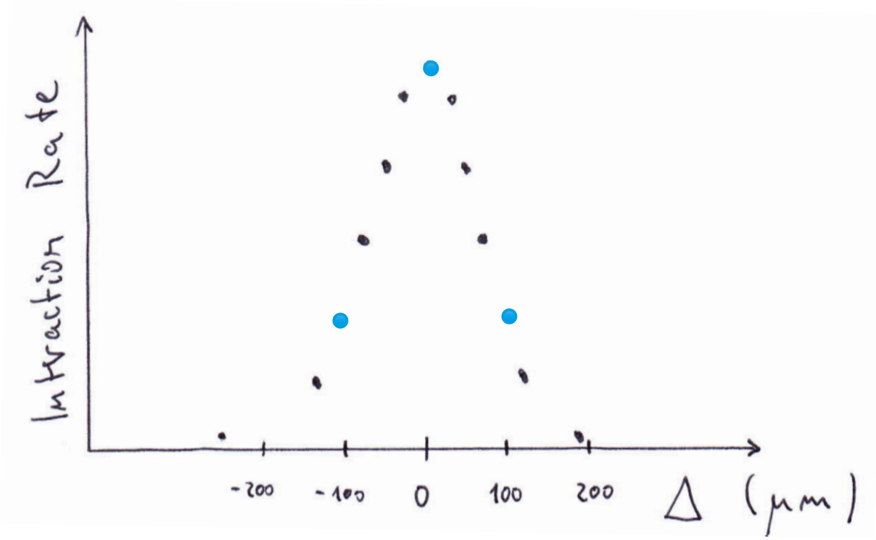




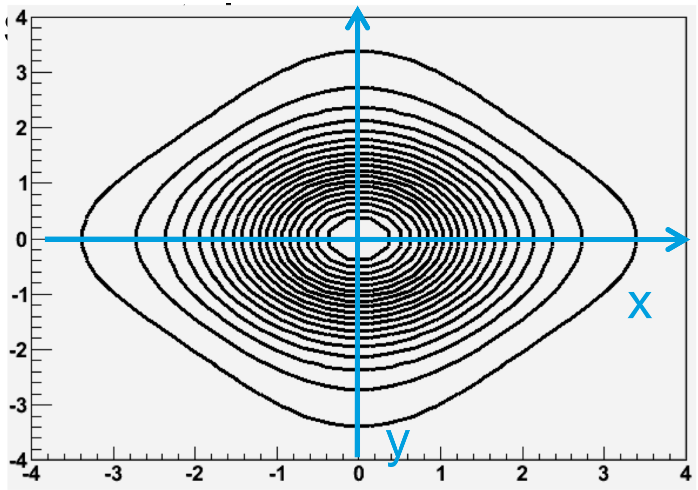
Luminosity calibration at colliders

van der Meer scans

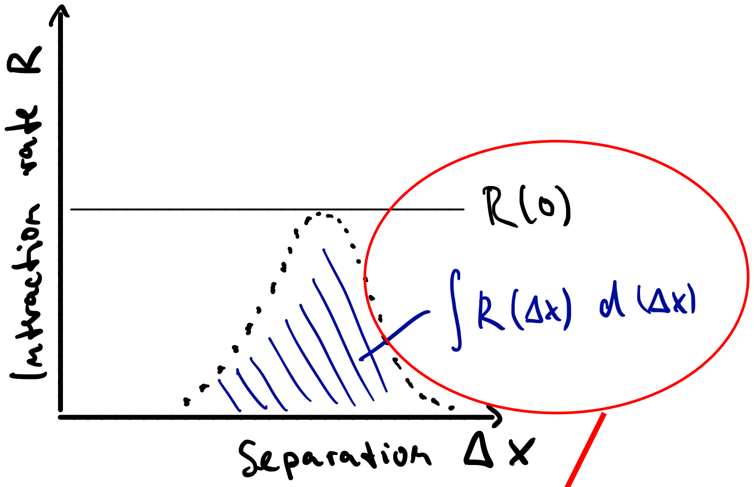




Scan x and y



Luminosity calibration at colliders

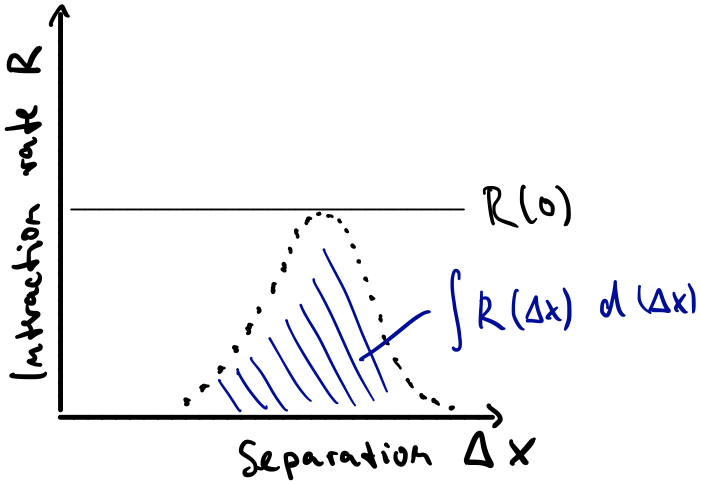


Bell-shaped scan curve parametrises the beam overlap integral, **irrespective of the functional form of** ρ!
Assume x and y beam shapes uncorrelated.

S.v.d.Meer

$$\int \rho_1(x)\, \rho_2(x)\, dx = \frac{R(0)}{\int R(\Delta x)\, d(\Delta x)}$$

Luminosity calibration at colliders

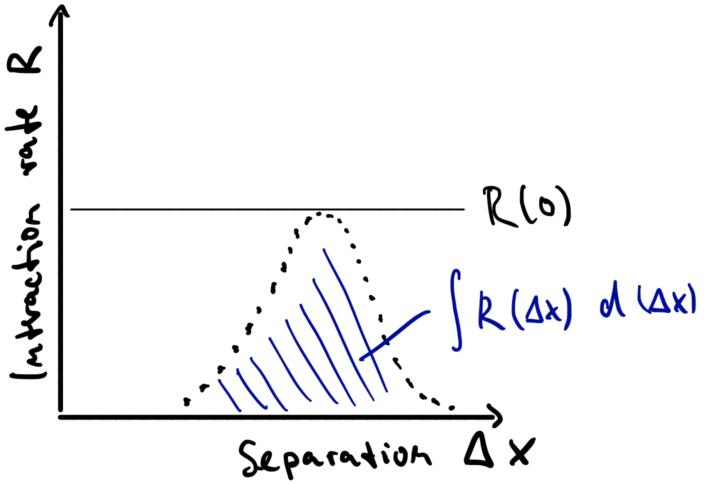


Bell-shaped scan curve parametrises the beam overlap integral, **irrespective of the functional form of ρ!**
Assume x and y beam shapes uncorrelated.

$$\int \rho_1(x)\,\rho_2(x)\,dx = \frac{R(0)}{\int R(\Delta x)\,d(\Delta x)}$$

$$\mathcal{L} = 2 N_1 N_2 n_b f_{LHC} \int \rho_1(x,y)\,\rho_2(x,y)\,dx\,dy$$

Luminosity calibration at colliders



Bell-shaped scan curve parametrises the beam overlap integral, **irrespective of the functional form of ρ!** Assume x and y beam shapes uncorrelated.

$$\mathcal{L} = \frac{\dot{R}}{\sigma} = \frac{\varepsilon \cdot \dot{R}}{\varepsilon \cdot \sigma} = \frac{\dot{R}_{\text{visible}}}{\sigma_{\text{visible}}}$$

↑ detector efficiency

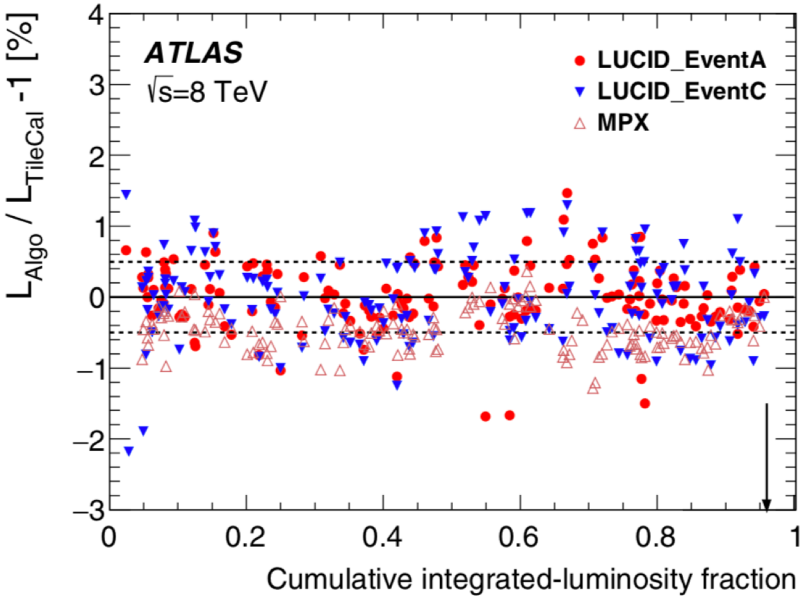
$$\int \rho_1(x)\,\rho_2(x)\,dx = \frac{R(0)}{\int R(\Delta x)\,d(\Delta x)}$$

$$\mathcal{L} = 2\,N_1 N_2\, n_b\, f_{LHC} \int \rho_1(x,y)\,\rho_2(x,y)\,dx\,dy$$

ATLAS absolute luminosity uncertainty

ATLAS, Eur. Phys. J. C (2016) 76

Different luminometers, all within 2%!



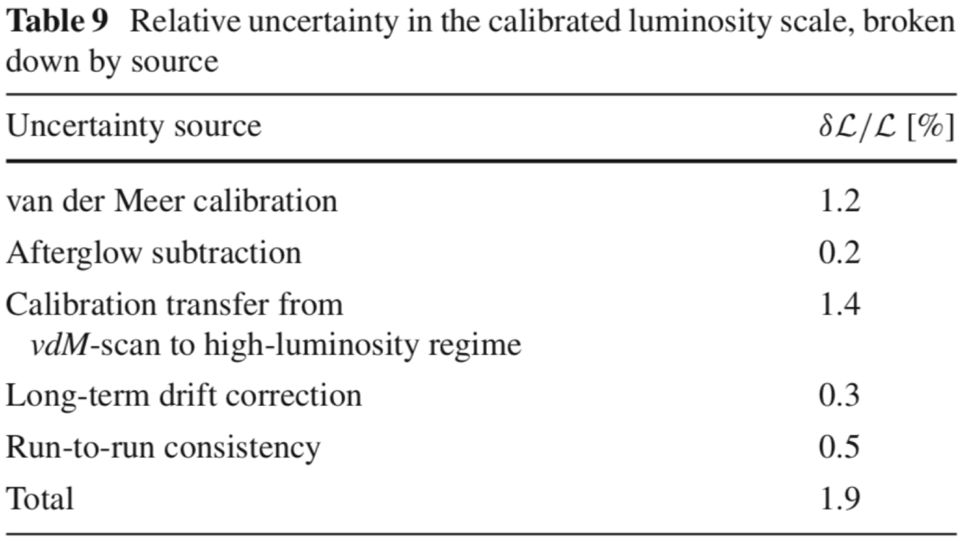


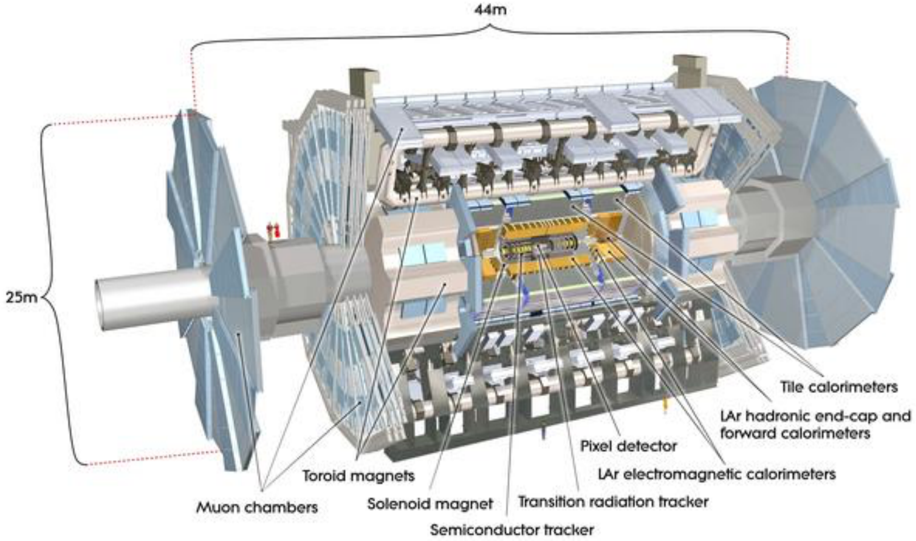
Table 9 Relative uncertainty in the calibrated luminosity scale, broken down by source

Uncertainty source	$\delta\mathcal{L}/\mathcal{L}$ [%]
van der Meer calibration	1.2
Afterglow subtraction	0.2
Calibration transfer from *vdM*-scan to high-luminosity regime	1.4
Long-term drift correction	0.3
Run-to-run consistency	0.5
Total	1.9

Works amazingly well!

ATLAS relevant cross section measurements

MBTS



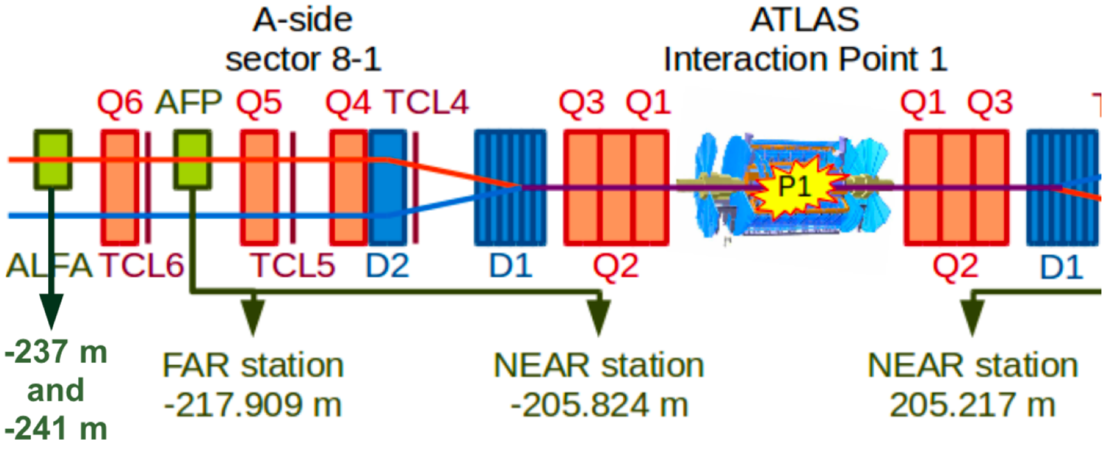
MBTS (Minimum Bias Trigger Scintillators)

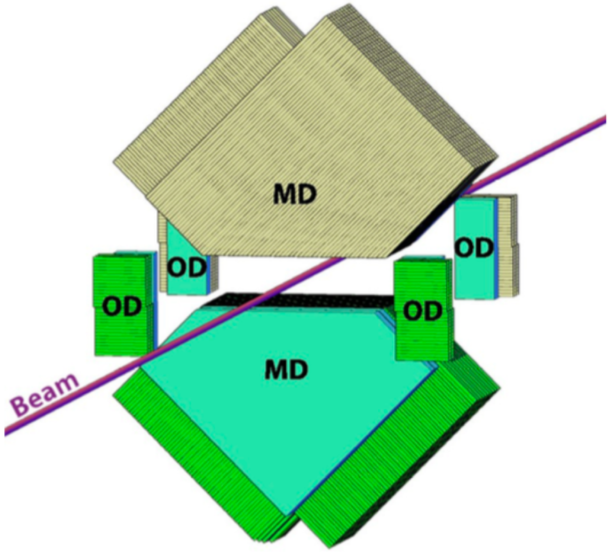
- two disks placed vertical to the beam on each side of the interaction point at 3.56 m
- divided into two rings in radial direction with 8 (or 4) sections in azimuth
- covers pseudorapidity range $2.08 < |\eta| < 3.86$ in

Main goal:
triggering minimum bias events, also used in measurement of inelastic cross section

ATLAS relevant cross section measurements

ALFA





ALFA (Absolute Luminosity For ATLAS)

- two arms
- two stations on each side, at 237 m and 241 m with two main and overlap detectors
- placed in Roman Pots
- scintillator fibres
- read out by Multi-Anode Photomultiplier Tubes
- 10 layers of fibres in each upper and lower main detector
- overlap detectors - 3 layers

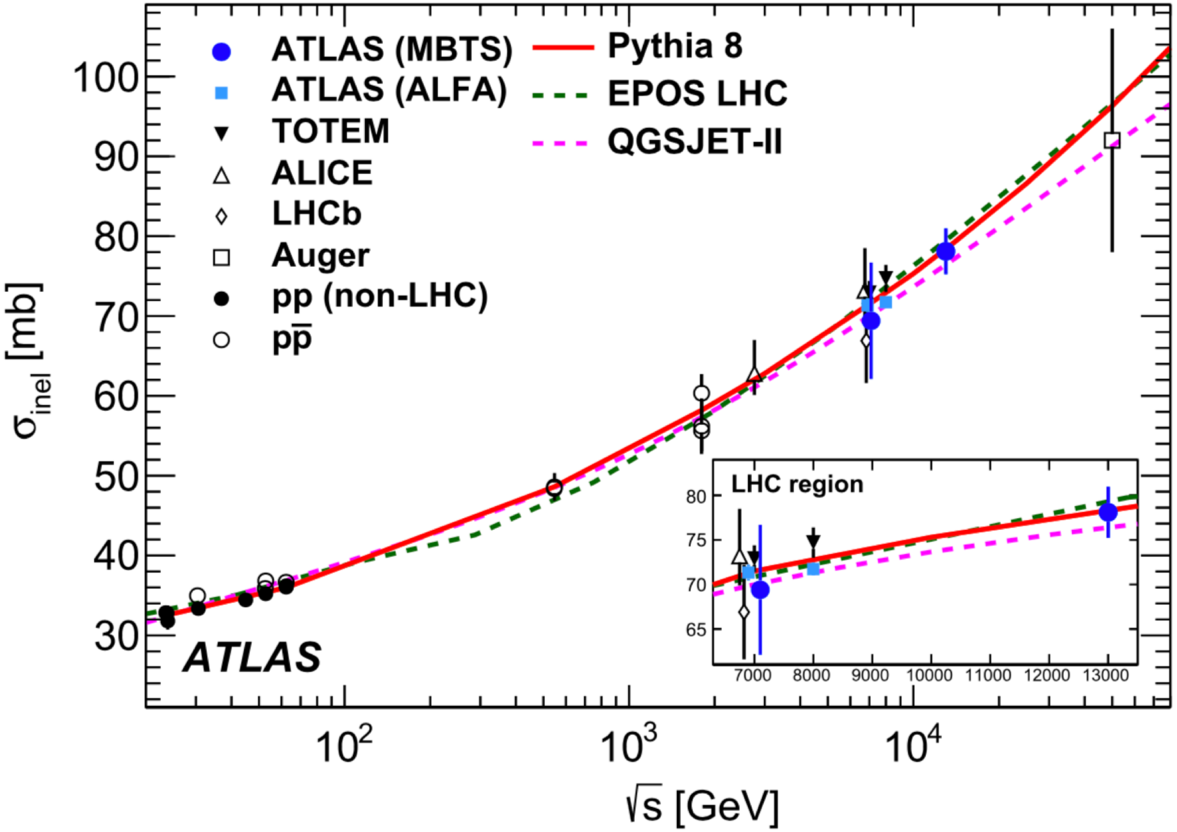
K.Wozniak, ISVHECRI 2018

Inelastic cross section at 7 and 13 TeV

Inelastic cross section

at 7 TeV (20.3 μb^{-1}):
σ_{inel} = 69.1 ±2.4 (exp.) ±6.9 (extr.) mb

at 13 TeV (60.1 μb^{-1}):
σ_{inel} = 78.1 ±0.6 (exp.) ±1.3 (lum.) ±2.6 (extr.) mb

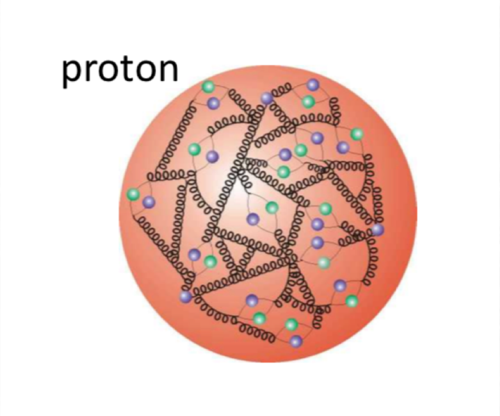


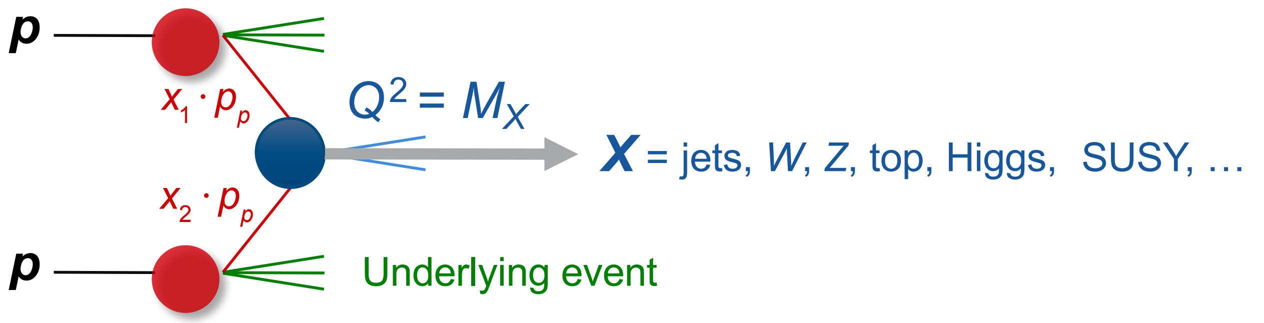
Achieving this precision is a big success.
Luminosity uncertainty also relevant for searches.

Nature Commun. 2 (2011) 463 (7 TeV)
Phys. Rev. Lett. 117 (2016) 182002 (13 TeV)
Nucl. Phys. B889 (2014) 486 (7 TeV)
Phys. Lett. B 761 (2016) 158 (8 TeV)

Dark matter at the LHC

Searches for weakly interacting particles

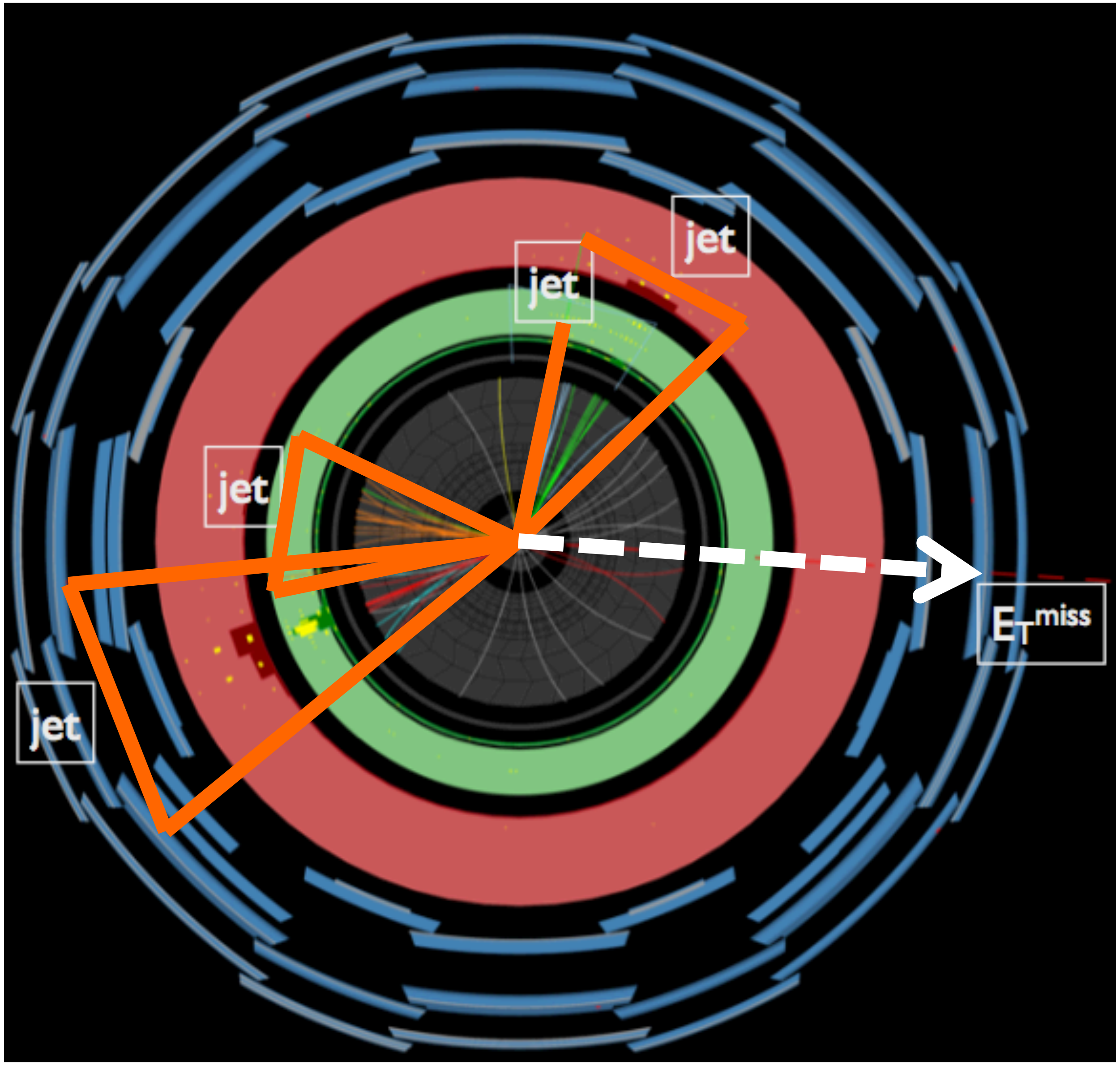




$Q^2 = M_X$

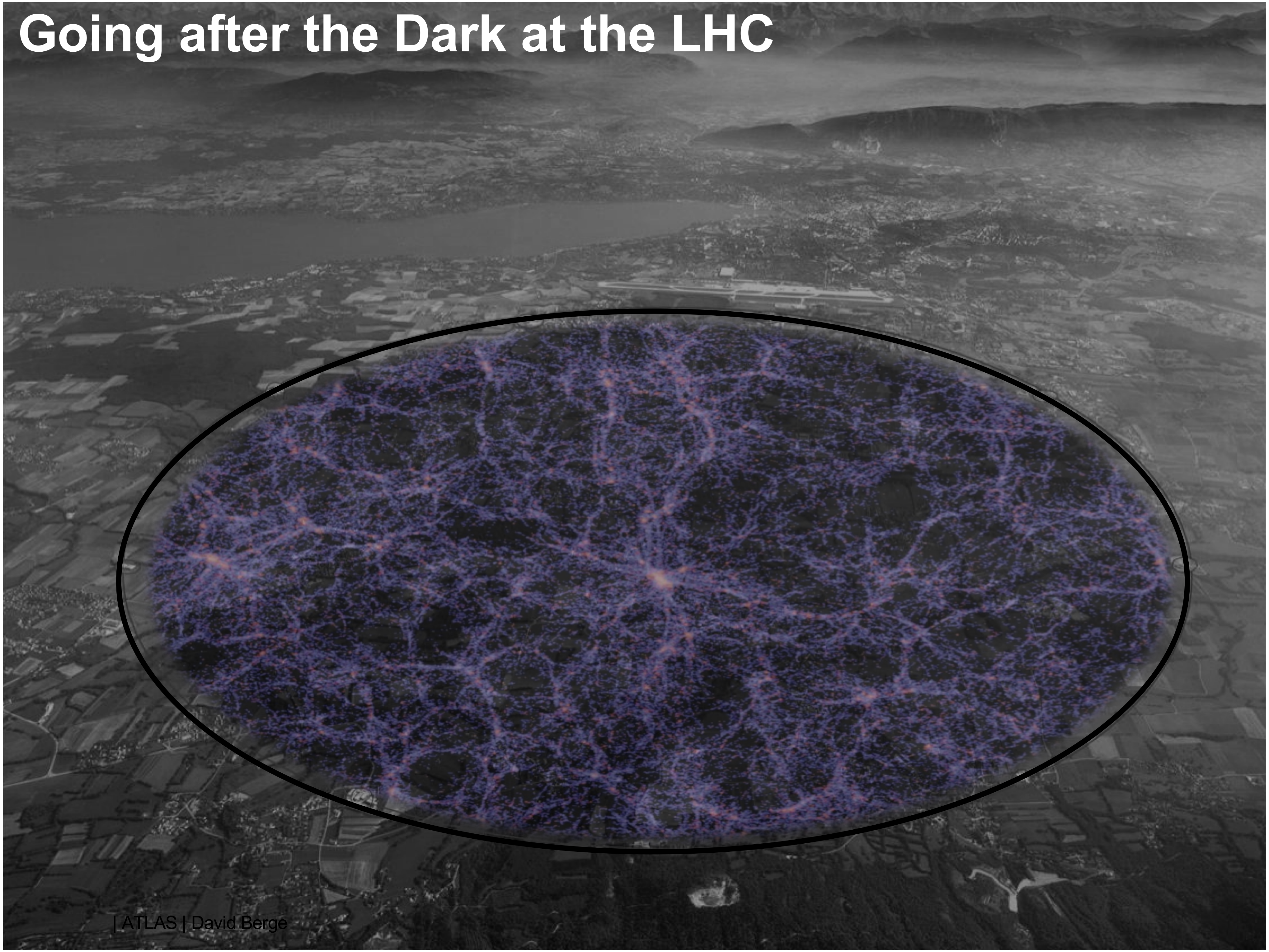
$\boldsymbol{X}$ = jets, W, Z, top, Higgs, SUSY, …

Underlying event

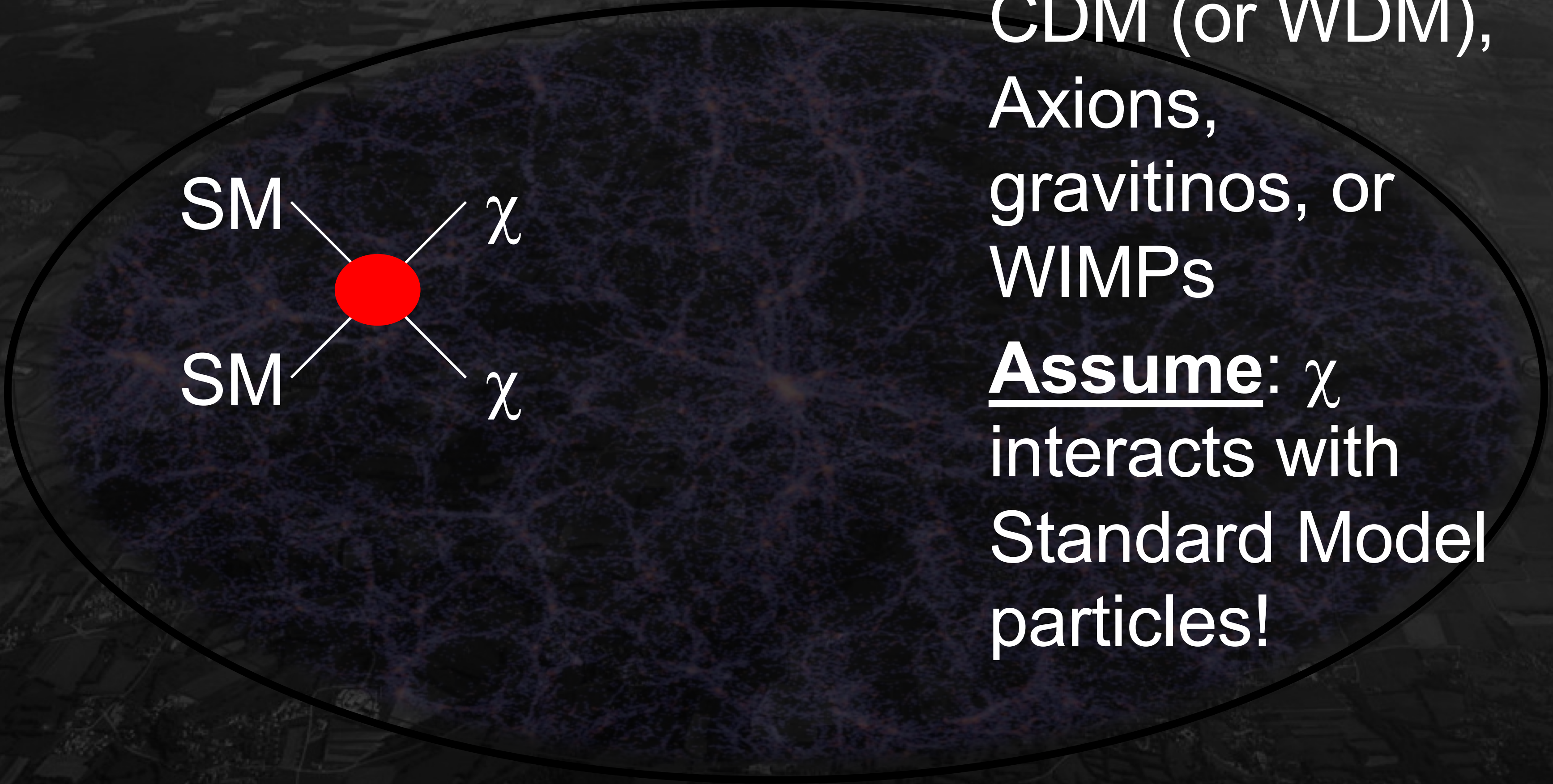


Rely on visible to detect invisible particles

Going after the Dark at the LHC



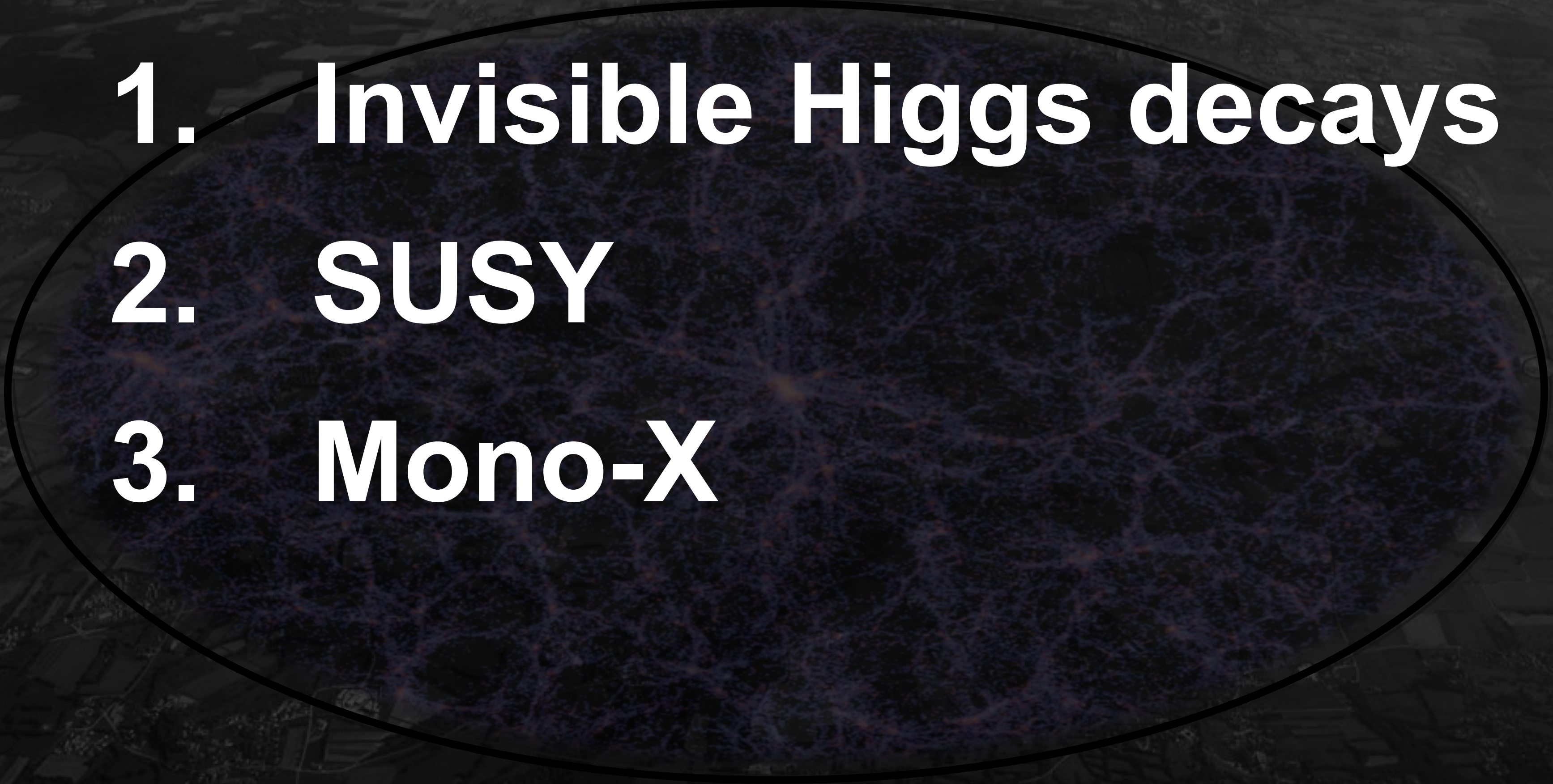
ASSUMPTIONS



DM particle χ: CDM (or WDM), Axions, gravitinos, or WIMPs

Assume: χ interacts with Standard Model particles!

3 TYPES of WIMP SEARCHES at LHC

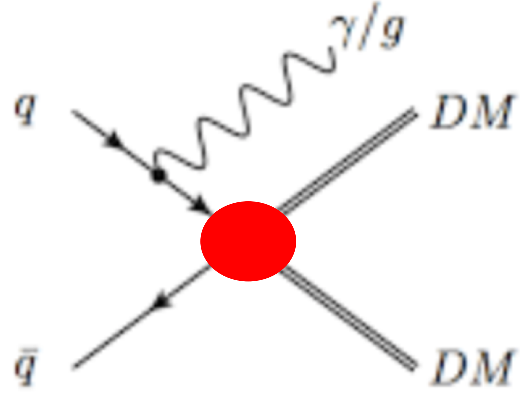


1. Invisible Higgs decays
2. SUSY
3. Mono-X

3 TYPES of WIMP SEARCHES at LHC

More sensitive to specific models
More reliant on model assumptions

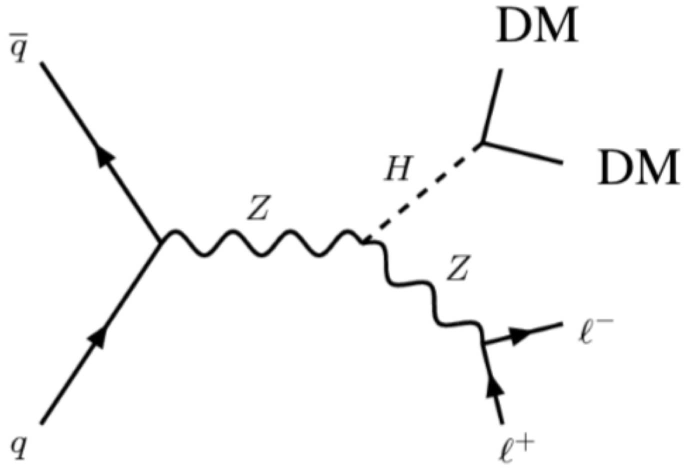
1. Invisible Higgs decays
2. SUSY
3. Mono-X



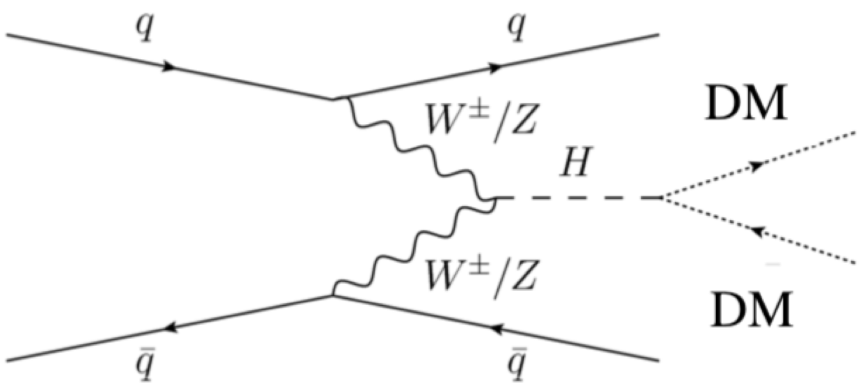
Fewer assumptions on models
“Only” assume WIMP miracle

Invisible Higgs decays

Higgs couples to DM and $m_H > 2\ m_\chi$

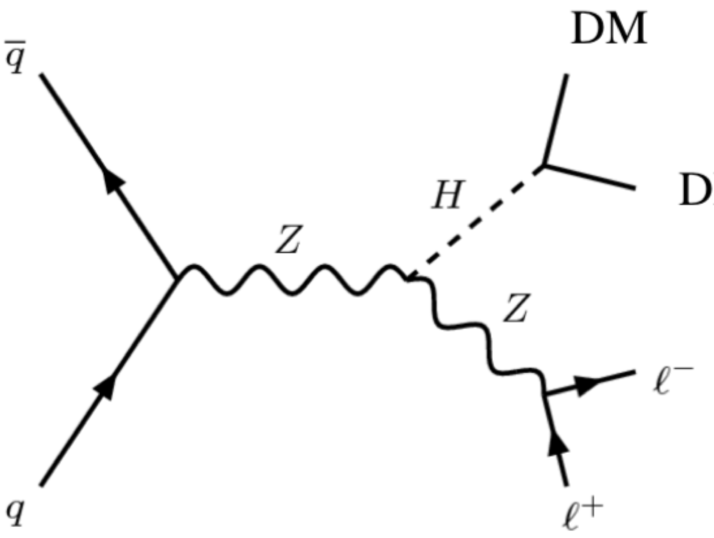


Z + dark matter

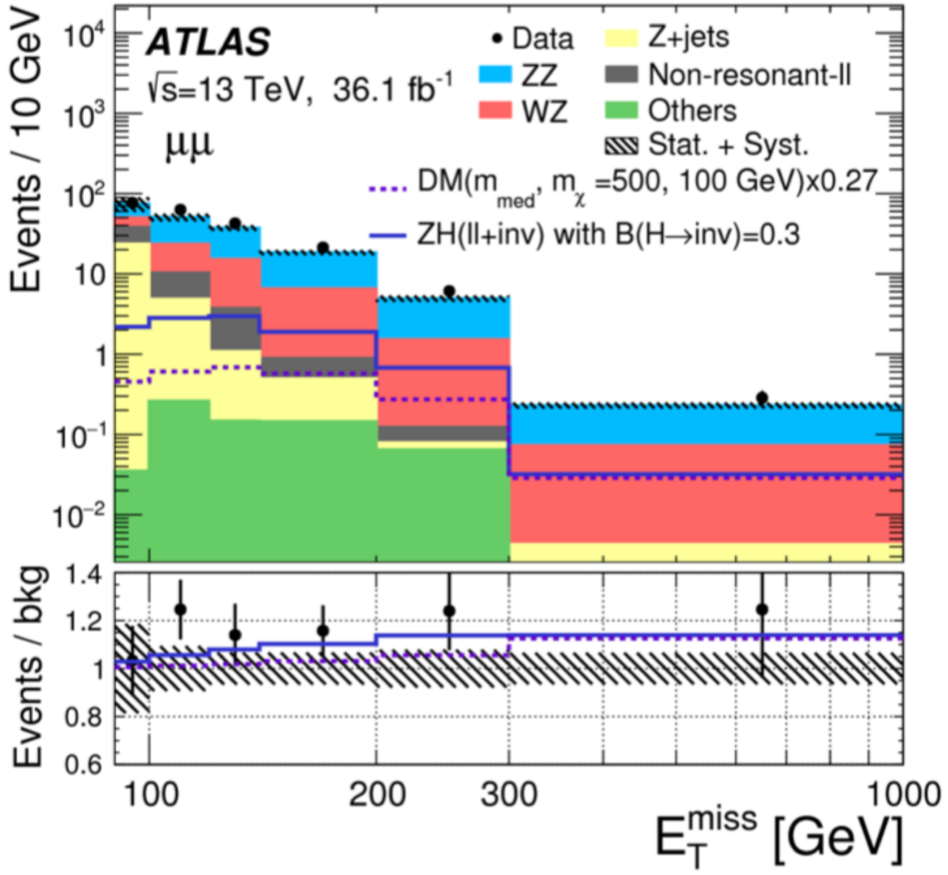


2 jets + dark matter

Invisible Higgs: Z + DM



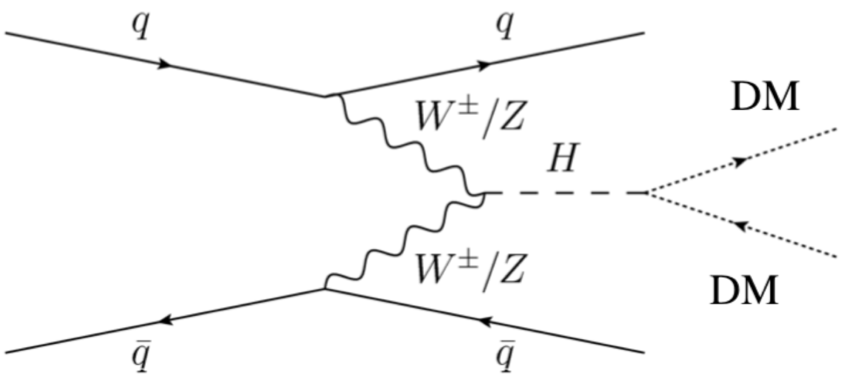
PLB 776 (2017) 318

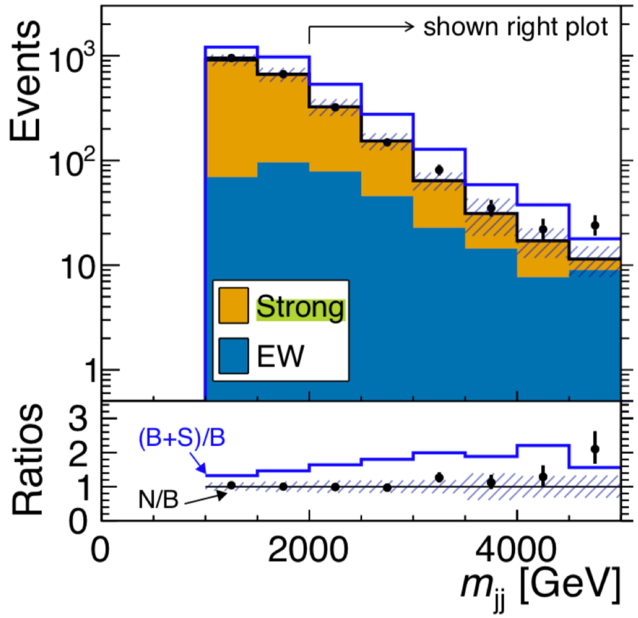


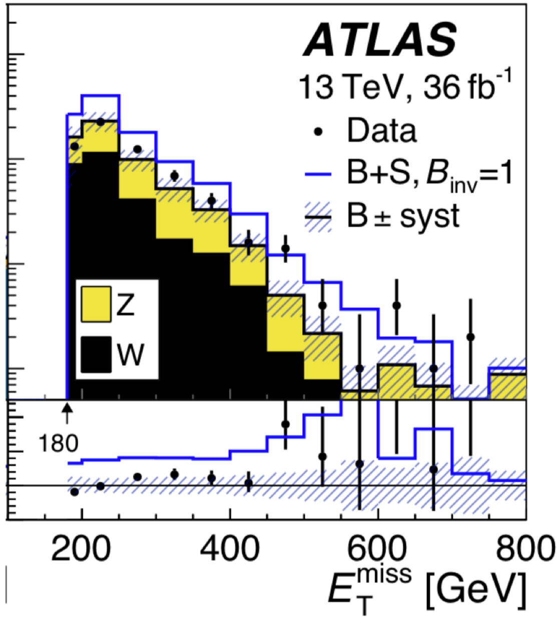
Higgs invisible width < 67% at 95% CL

Invisible Higgs: 2 jets + DM

arXiv:1809.06682







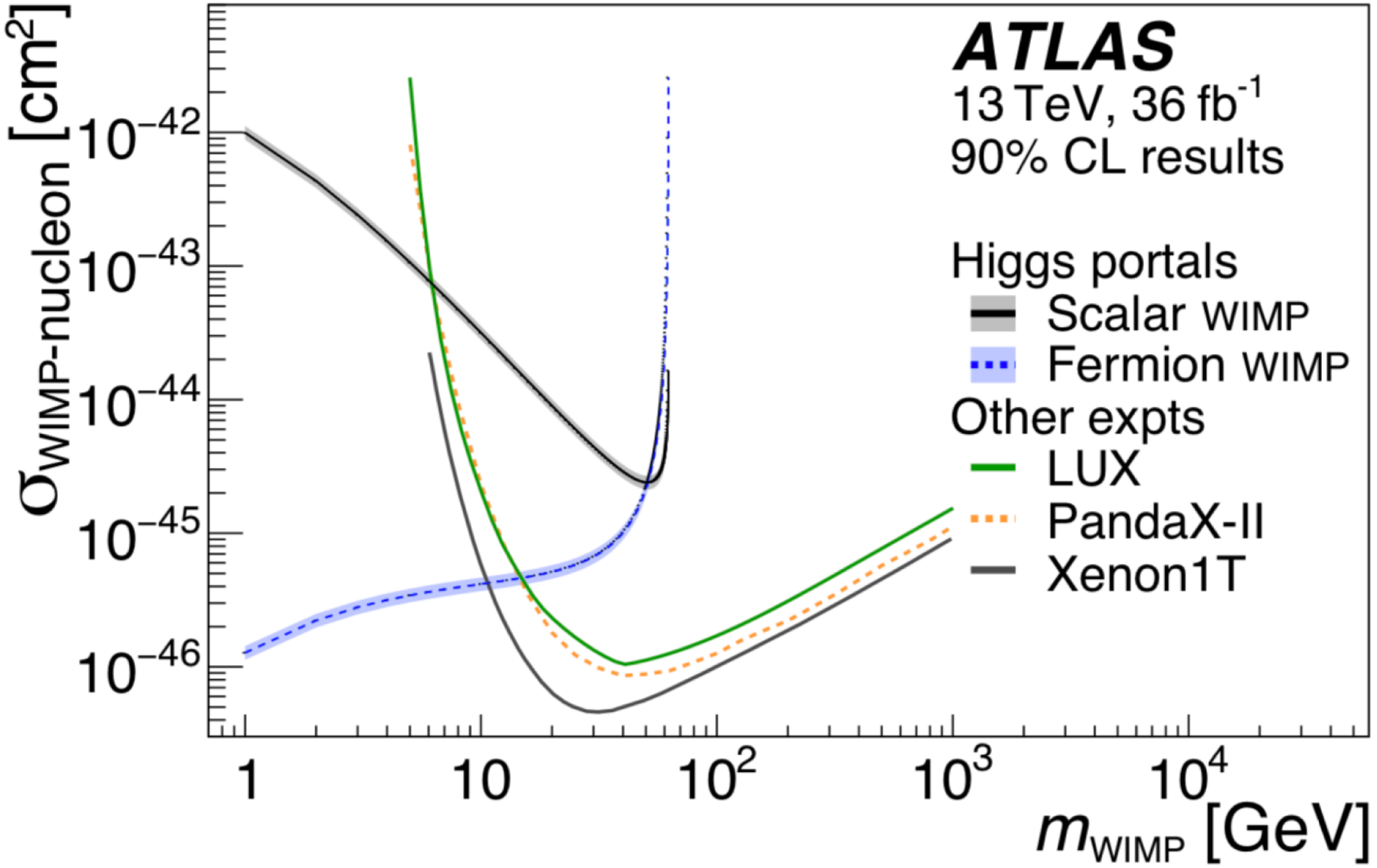
Higgs invisible width < 37% at 95% CL

Direct searches vs Higgs constraints

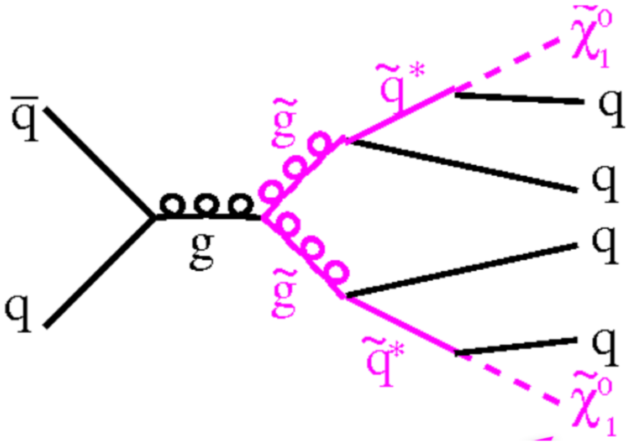
Assume Higgs the only mediator

In these models, low-mass advantage LHC

High-mass advantage direct searches



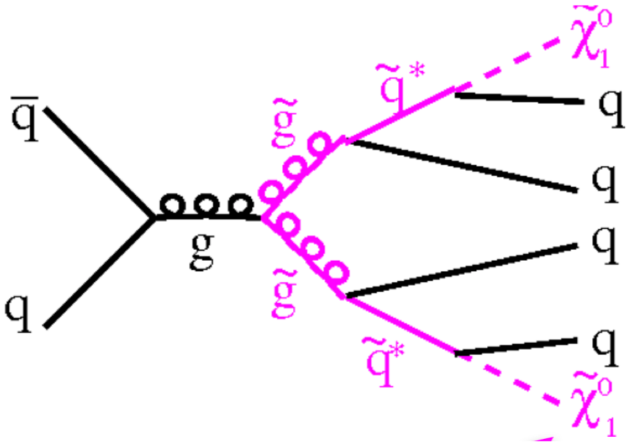
SUSY dark matter searches



SUSY dark matter produced in high-multiplicity decay chains of supersymmetric heavy particles (e.g. gluinos).

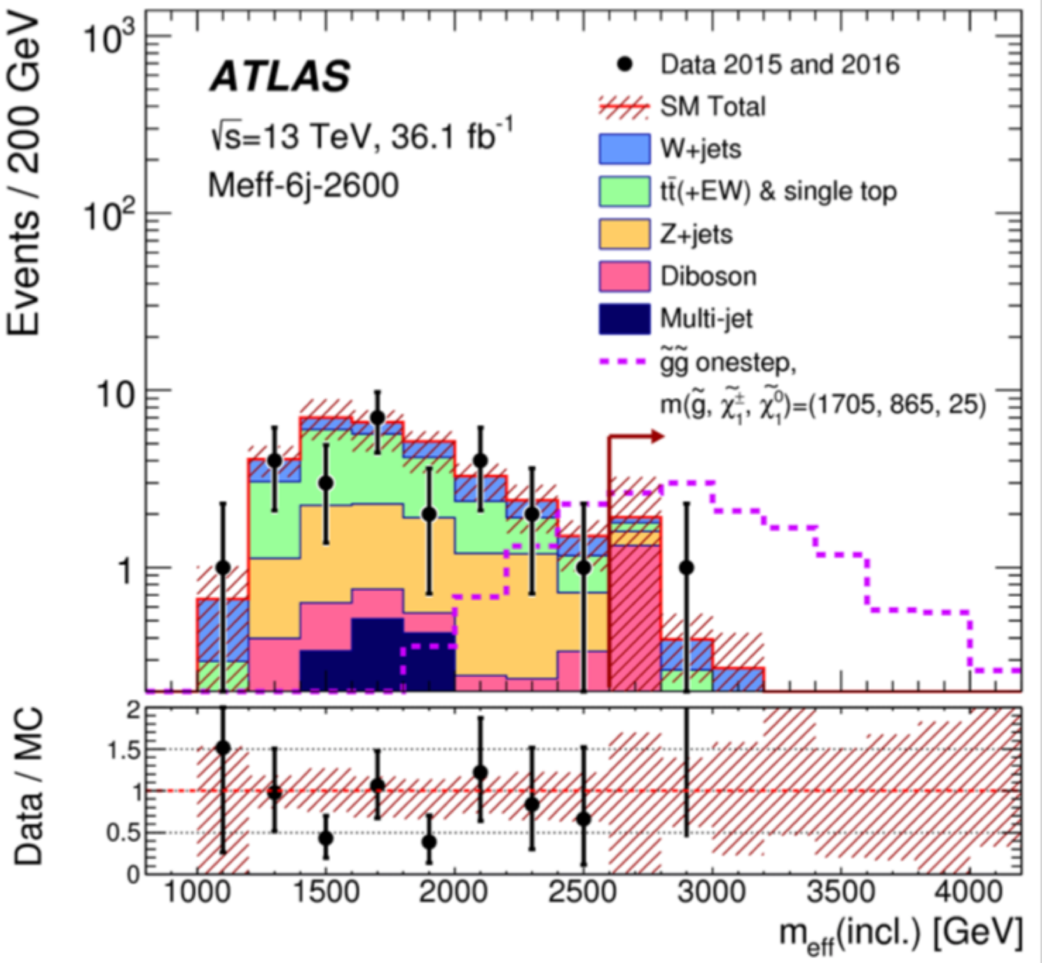
Large missing E_T plus jets

SUSY dark matter searches



Large missing E_T plus jets

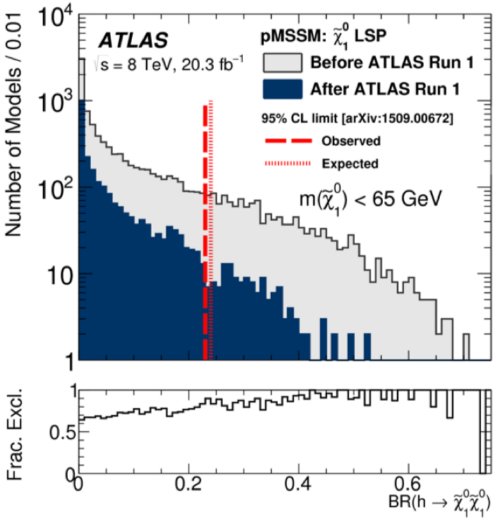
Phys. Rev. D 97 (2018) 112001



m_{eff} = missing E_T + Sum jets pt

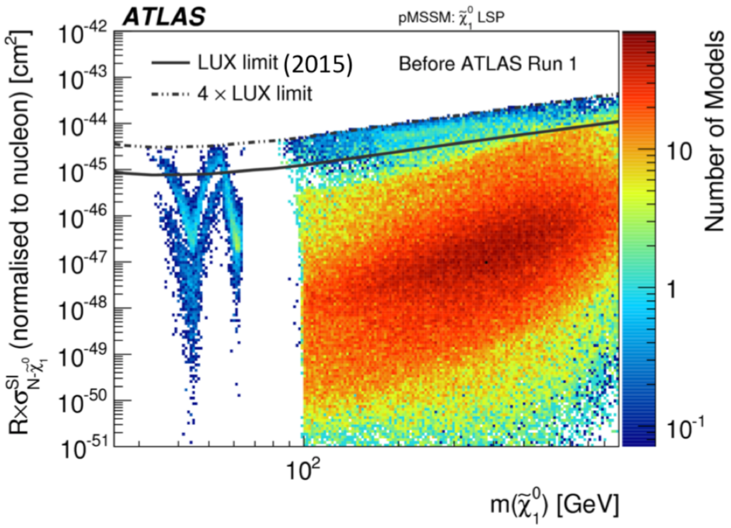
Impact of SUSY searches

Higgs invisible branching ratio



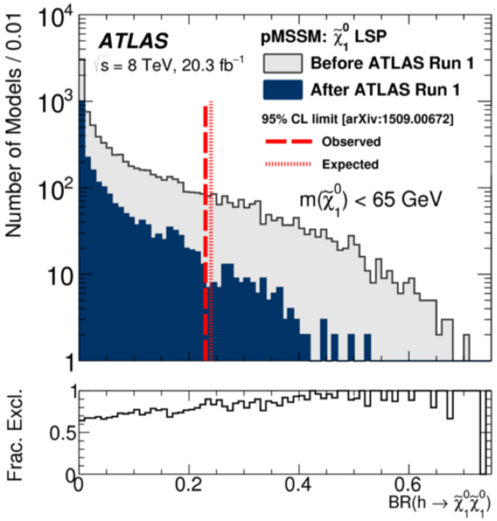
JHEP 10 (2015) 134

WIMP-nucleon cross section



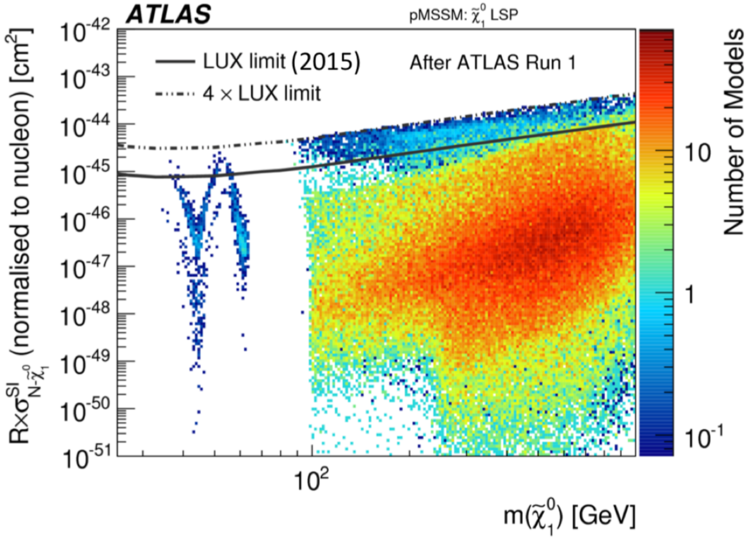
Impact of SUSY searches

Higgs invisible branching ratio



JHEP 10 (2015) 134

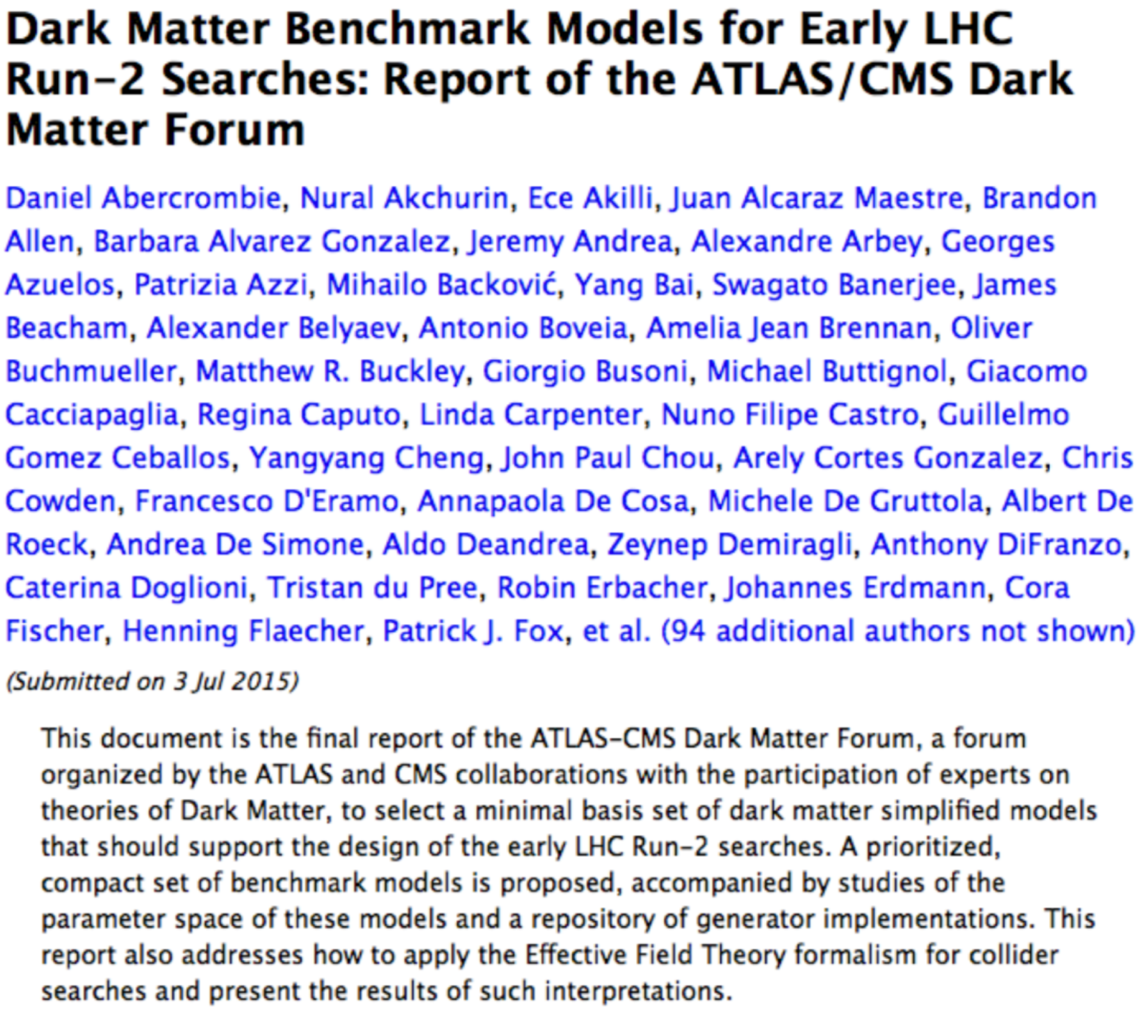
WIMP-nucleon cross section



ATLAS SUSY Public Results

Generic mono-X searches

Standardised searches: LHC dark matter working group,
http://lpcc.web.cern.ch/content/lhc-dm-wg-wg-dark-matter-searches-lhc



Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillelmo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristan du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, et al. (94 additional authors not shown)

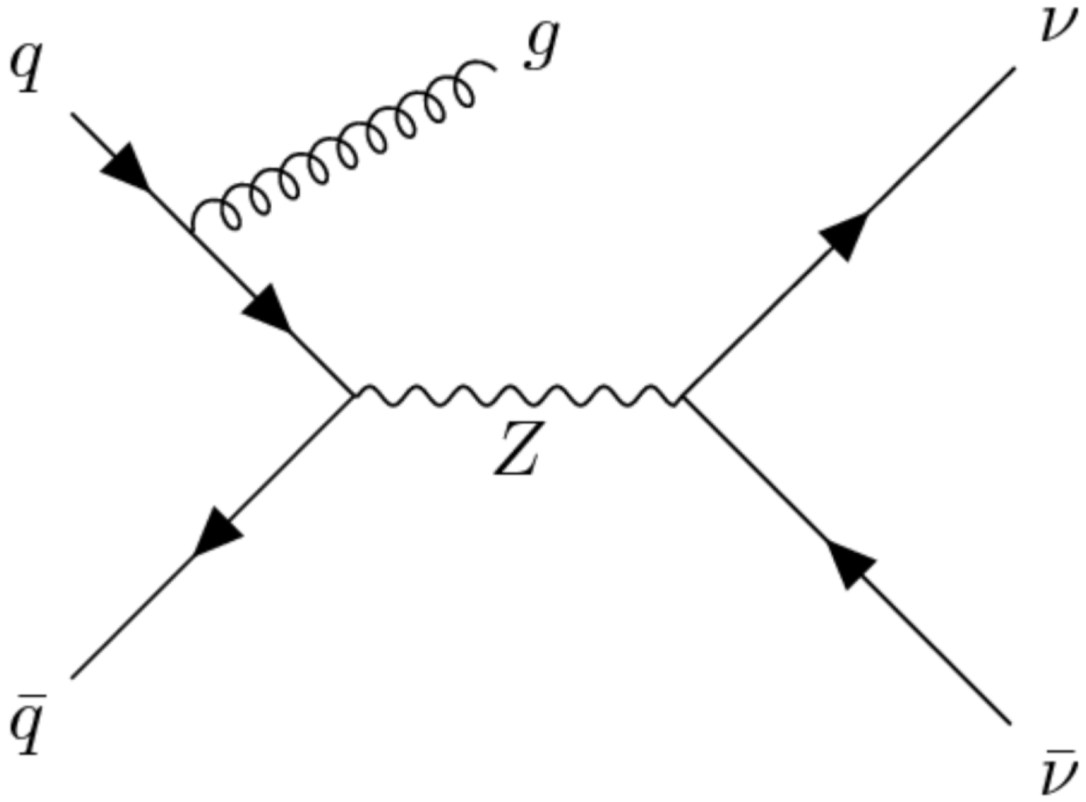
(Submitted on 3 Jul 2015)

This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum organized by the ATLAS and CMS collaborations with the participation of experts on theories of Dark Matter, to select a minimal basis set of dark matter simplified models that should support the design of the early LHC Run-2 searches. A prioritized, compact set of benchmark models is proposed, accompanied by studies of the parameter space of these models and a repository of generator implementations. This report also addresses how to apply the Effective Field Theory formalism for collider searches and present the results of such interpretations.

arXiv:1507.00966

LHC Production of invisible particles

Standard Model Background

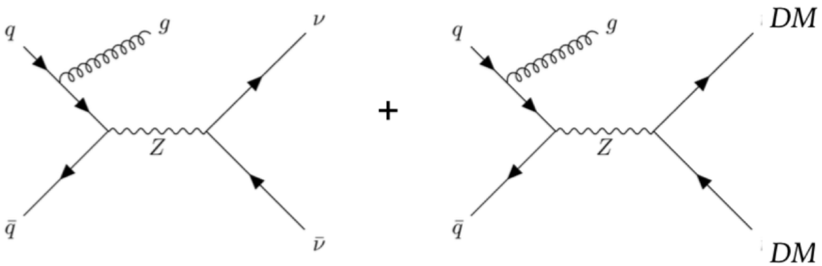


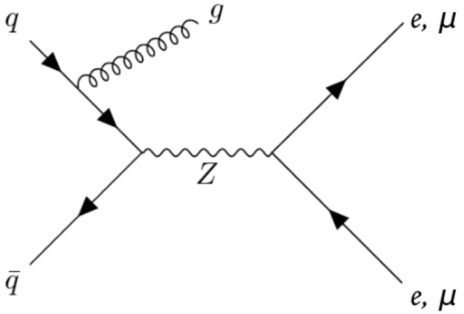
Credits C.Doglioni

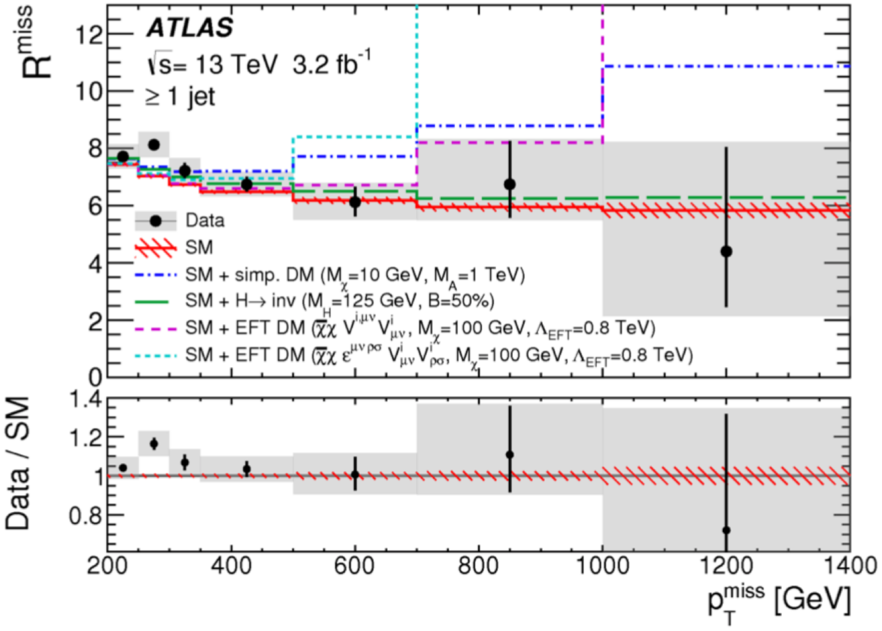
LHC Production of invisible particles

Standar Model Background

$$R^{\text{miss}} = \frac{\sigma_{\text{fid}}\left(p_{\text{T}}^{\text{miss}} + \text{jets}\right)}{\sigma_{\text{fid}}\left(\ell^{+}\ell^{-} + \text{jets}\right)}$$





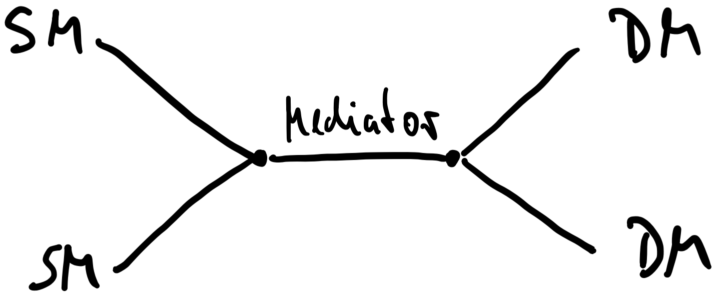


Eur. Phys. J. C 77 (2017) 765

Credits C.Doglioni

Generic mono-X searches

Search for DM pair or mediator directly (resonance search)



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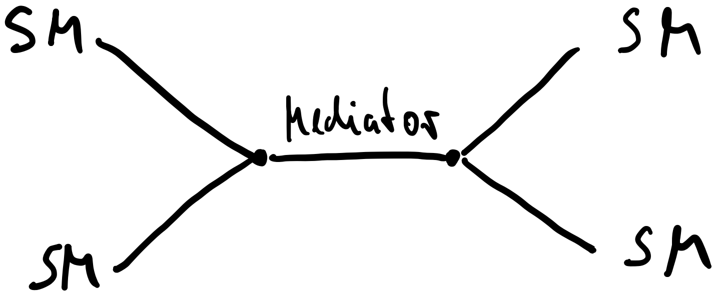
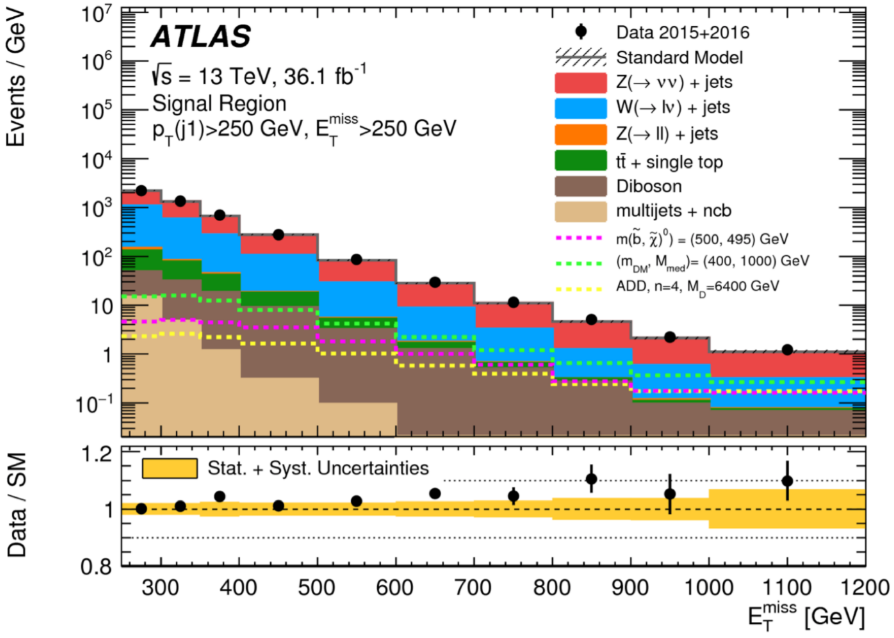
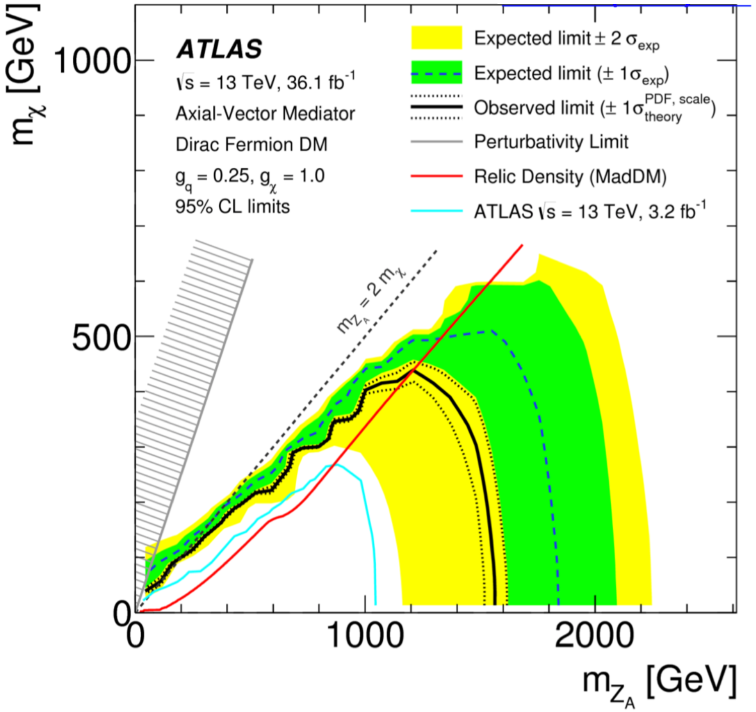


Generic mono-X searches

Search for DM pair or mediator directly (resonance search)

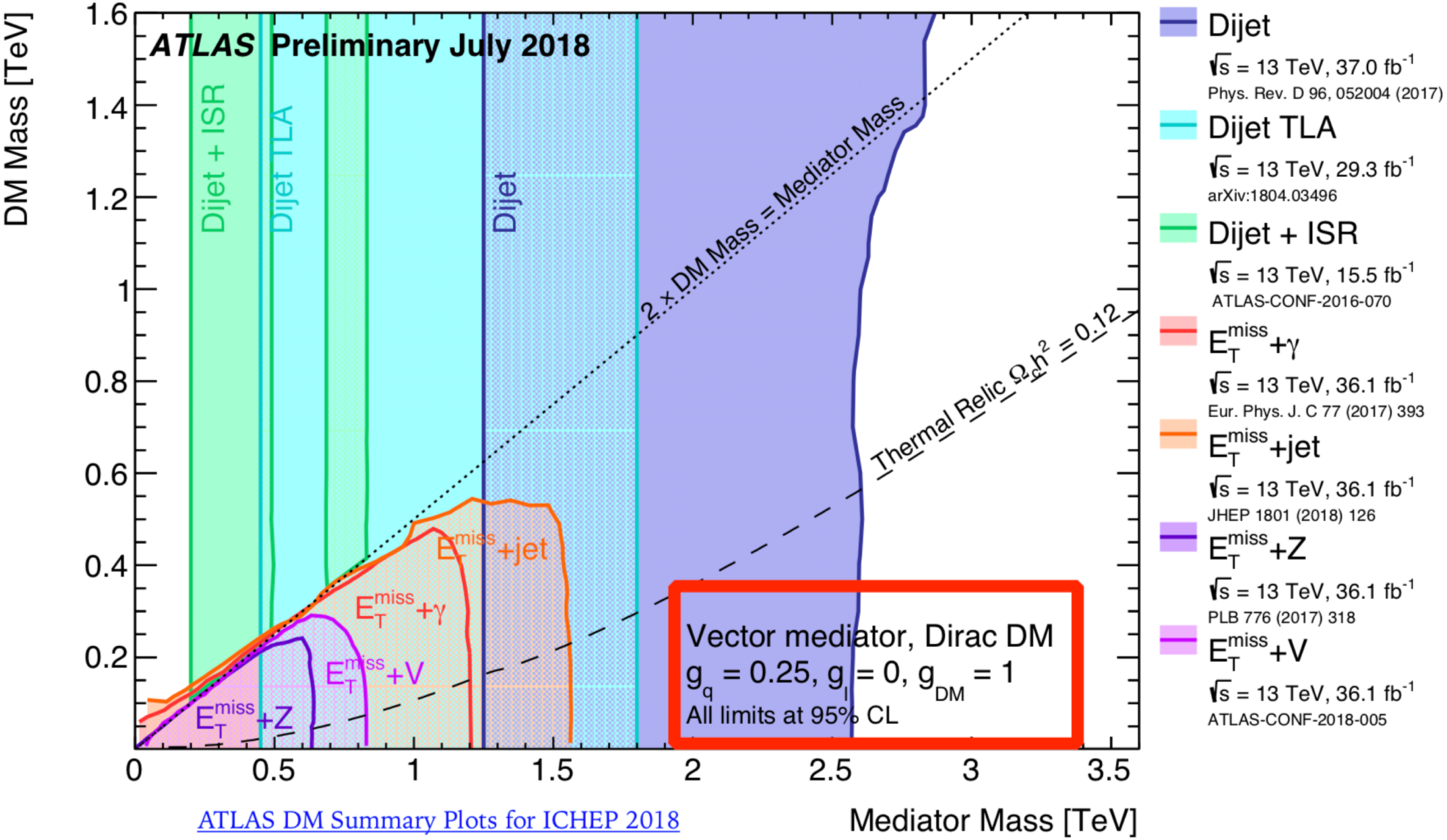
JHEP 01 (2018) 126





Generic mono-X searches

Search for DM pair or mediator directly (resonance search)



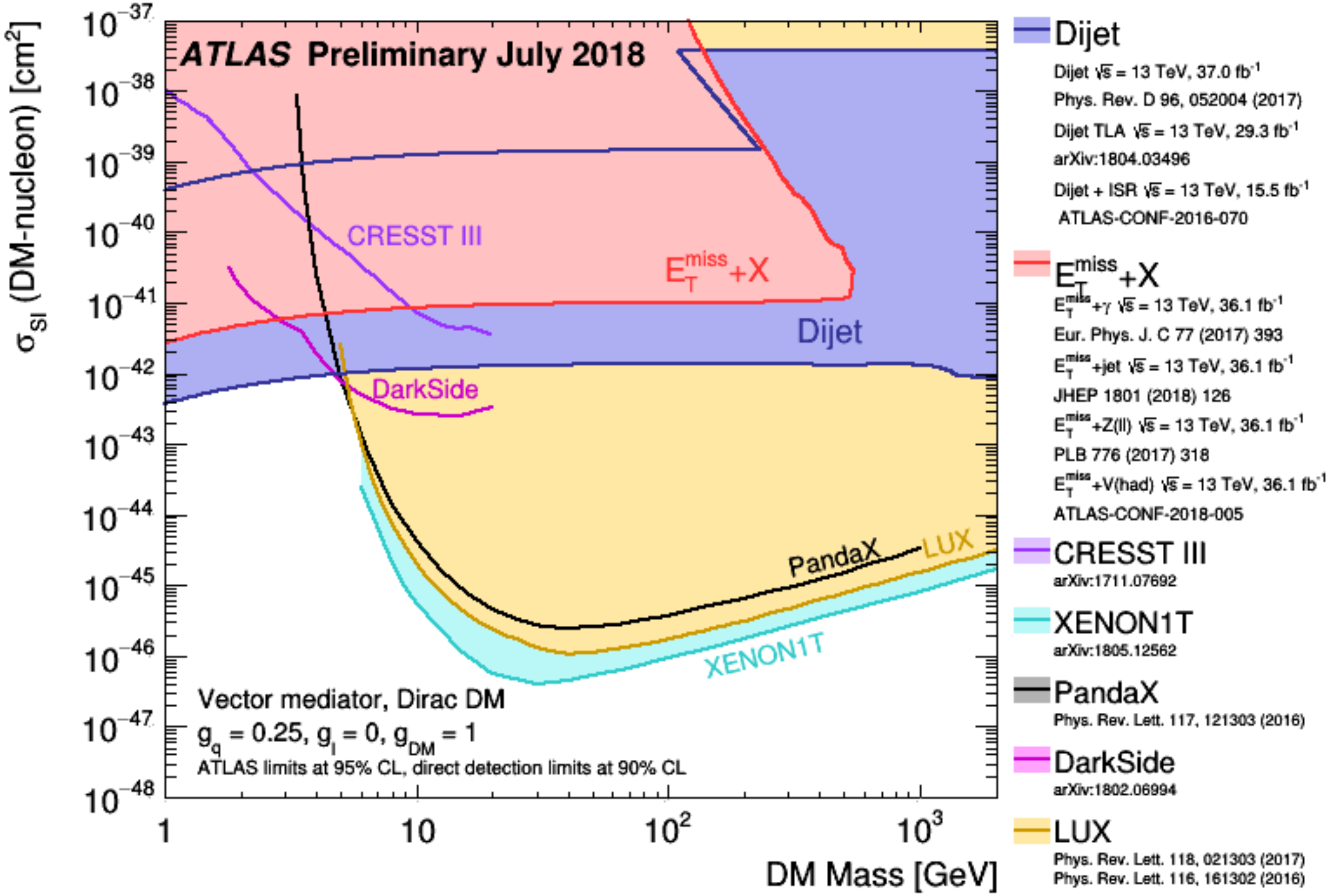
ATLAS DM Summary Plots for ICHEP 2018

Credits C.Doglioni

Complementarity with direct searches

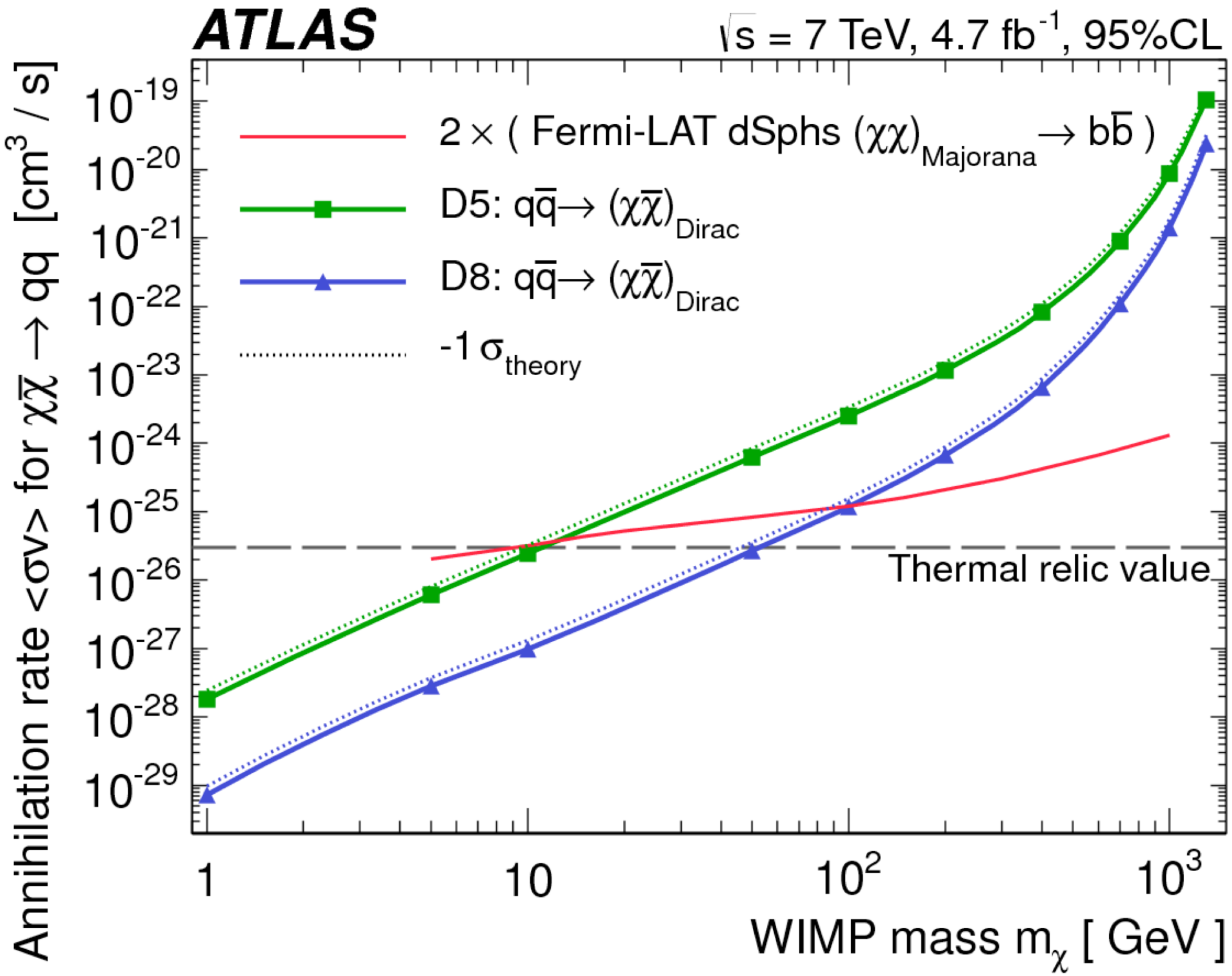
Valid only in the context of the chosen model / parameter set

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/



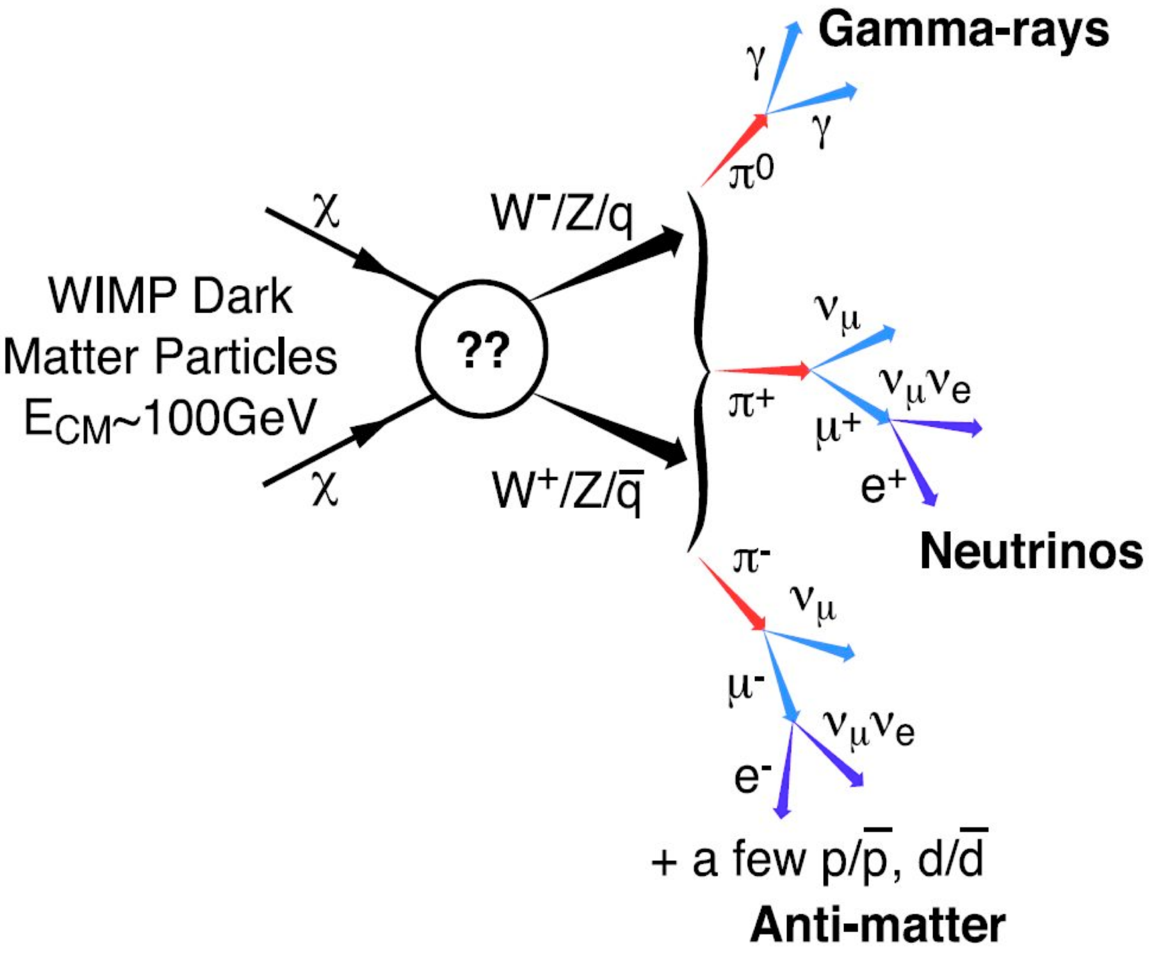
Complementarity with indirect searches

Valid only for very specific assumptions



arXiv:1210.4491

Dark matter shining in gamma rays

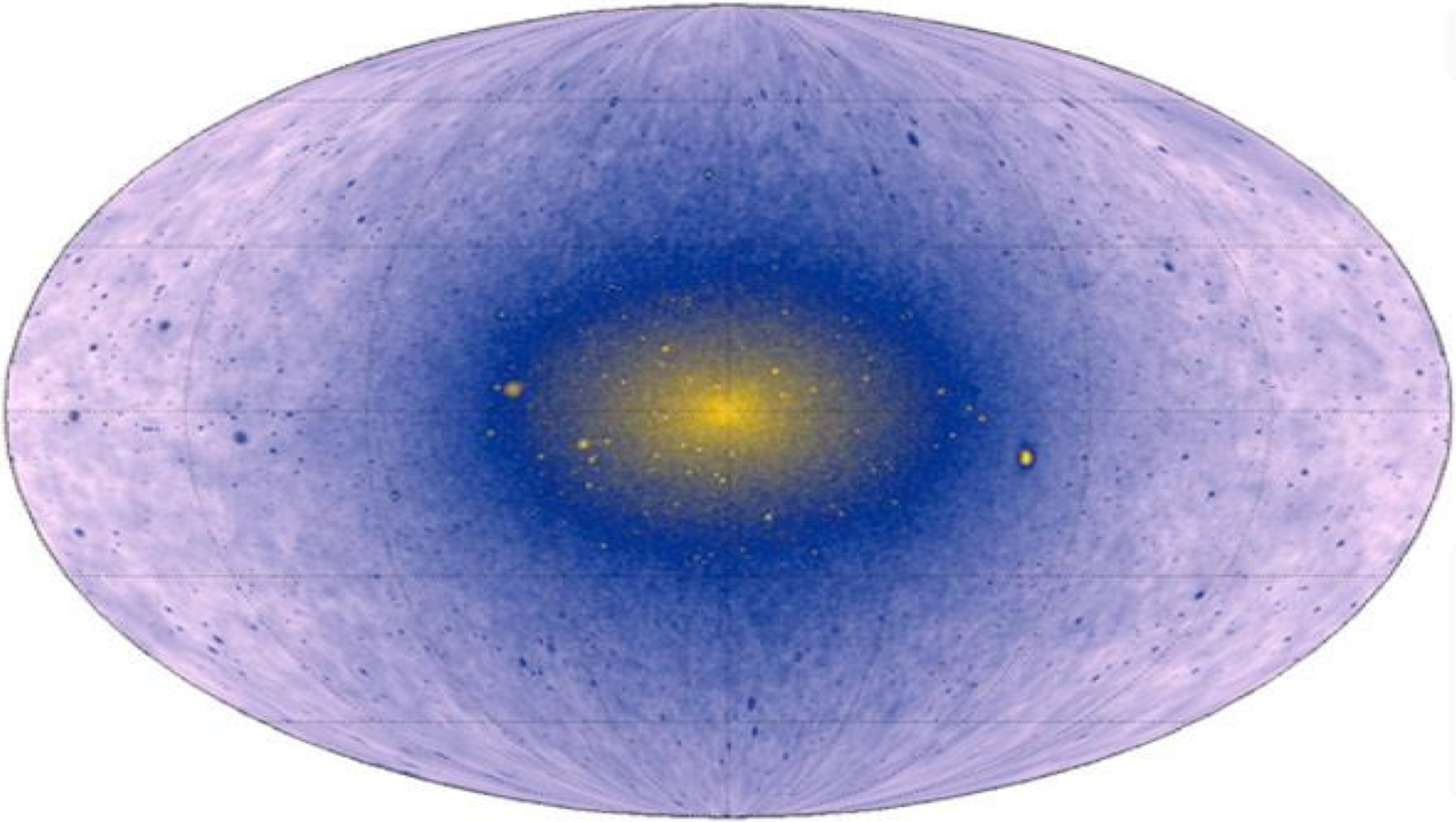


Dark matter shining in gamma rays

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{dE}_\gamma} = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2\mathrm{m}_{\mathrm{WIMP}}^2}\sum_f \frac{\mathrm{dN}_\gamma^f}{\mathrm{dE}_\gamma}\mathrm{B}_f}_{\text{`Particle Physics'}} \times \underbrace{\int_{\Delta\Omega}\mathrm{d}\Omega' \int_{\mathrm{los}} \rho^2 \mathrm{d}l(r,\theta')}_{\text{`Astrophysics' or } J(E)}$$

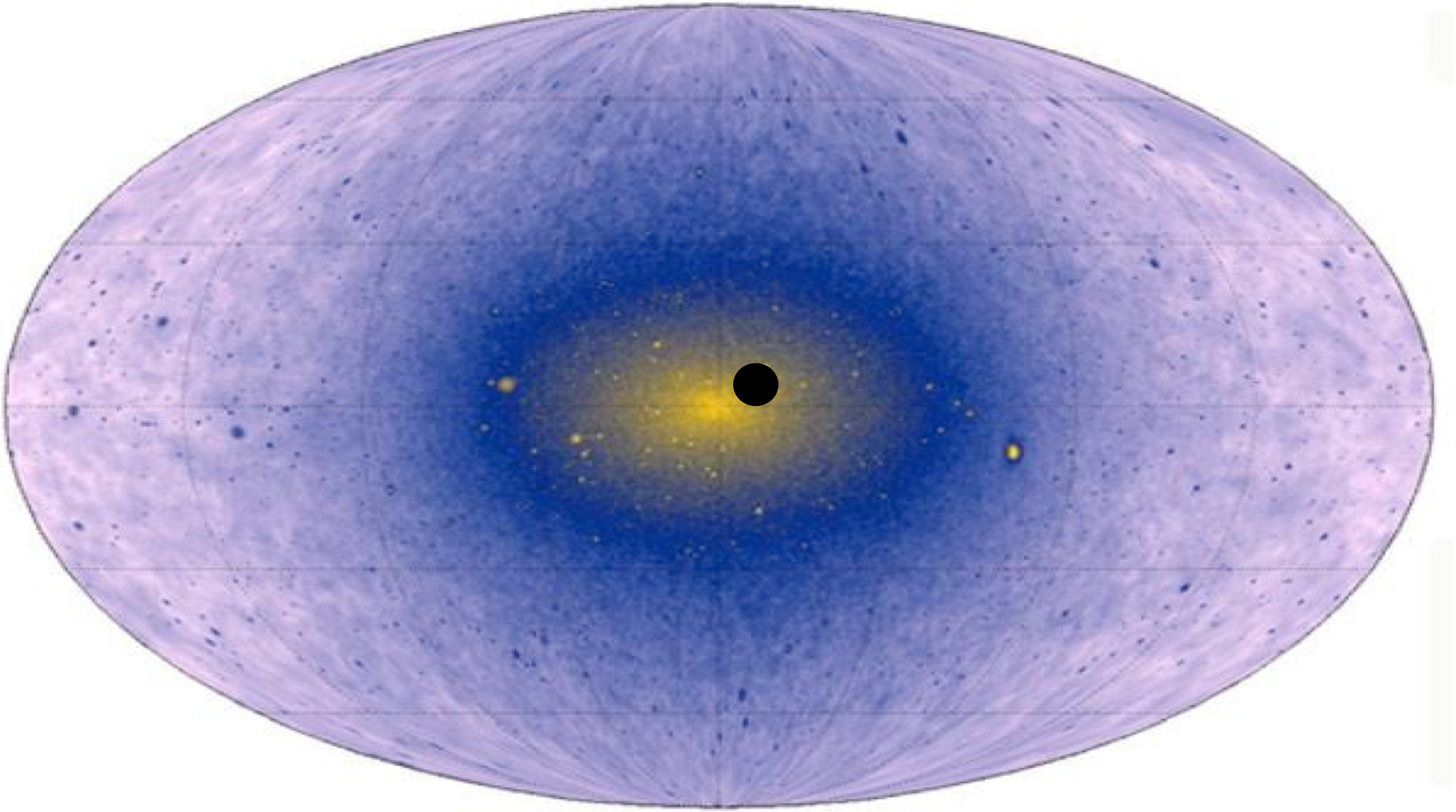
Dark matter in the sky

Simulated gamma rays from dark matter annihilations

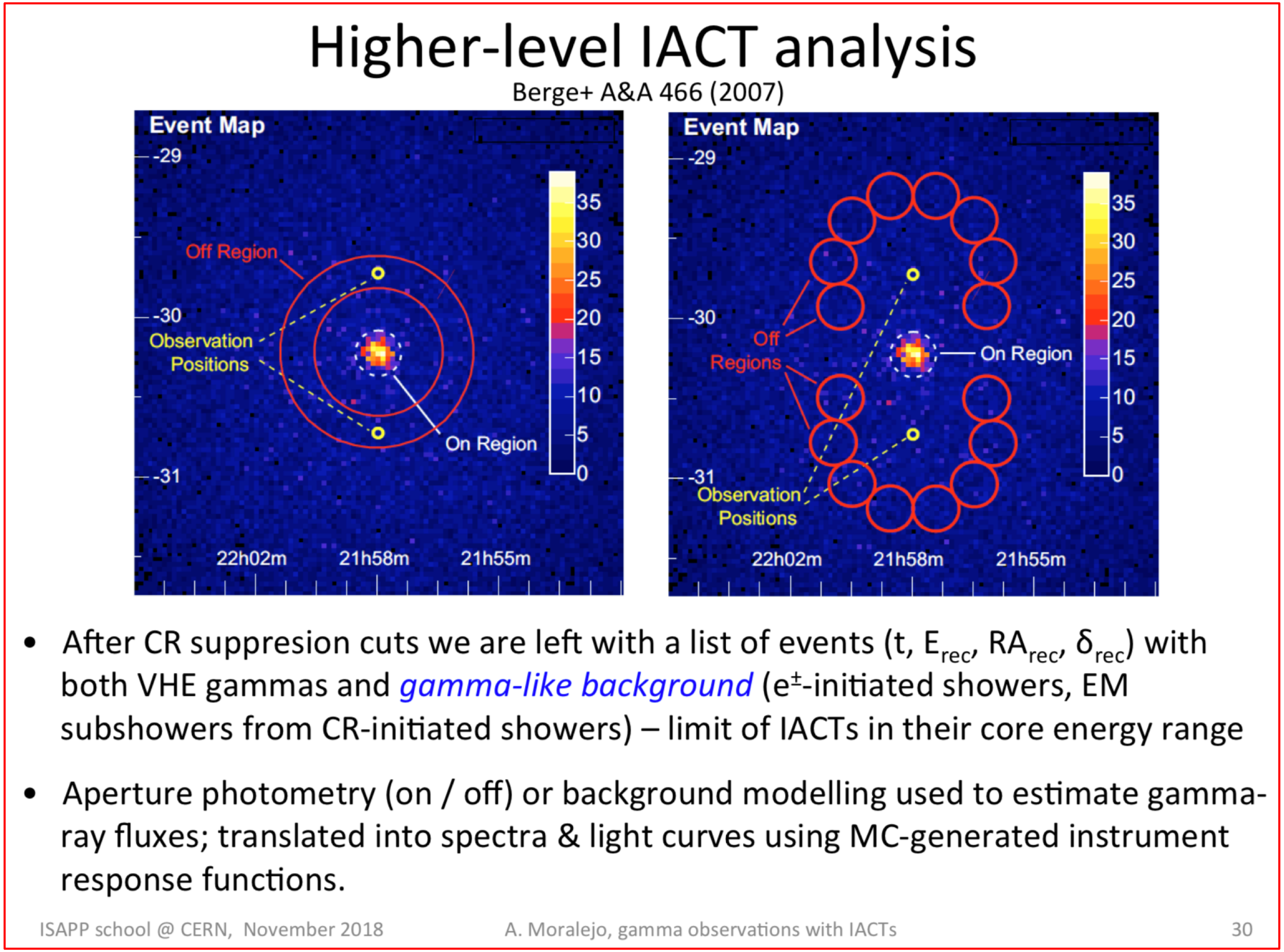


Dark matter in the sky

Simulated gamma rays from dark matter annihilations



Remember yesterday‘s lecture by Abelardo



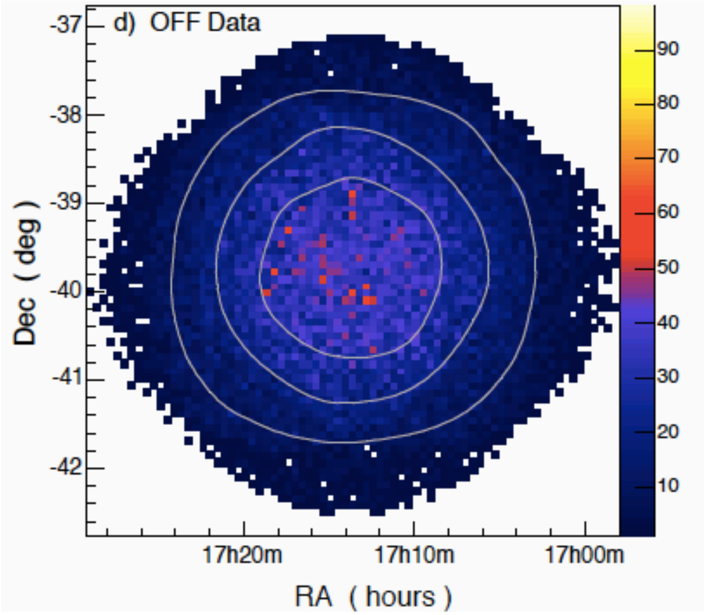
Higher-level IACT analysis

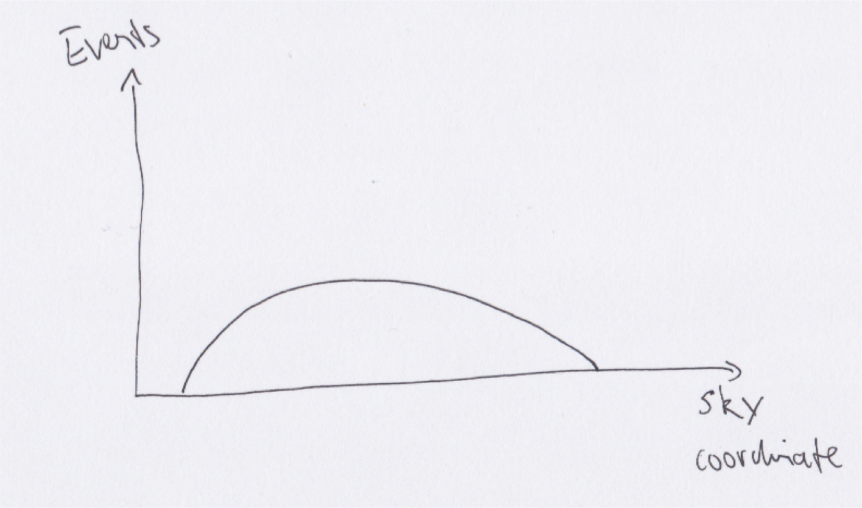
Berge+ A&A 466 (2007)

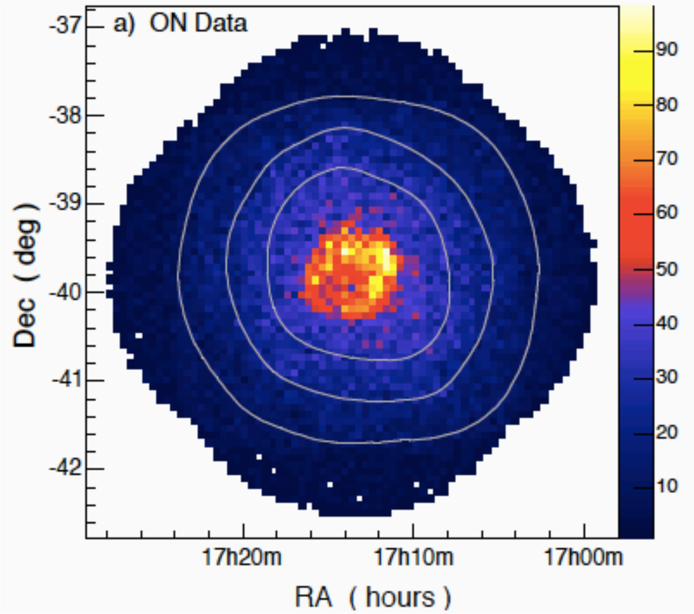
- After CR suppresion cuts we are left with a list of events (t, E_{rec}, RA_{rec}, δ_{rec}) with both VHE gammas and *gamma-like background* ($e^{\pm}$-initiated showers, EM subshowers from CR-initiated showers) – limit of IACTs in their core energy range
- Aperture photometry (on / off) or background modelling used to estimate gamma-ray fluxes; translated into spectra & light curves using MC-generated instrument response functions.

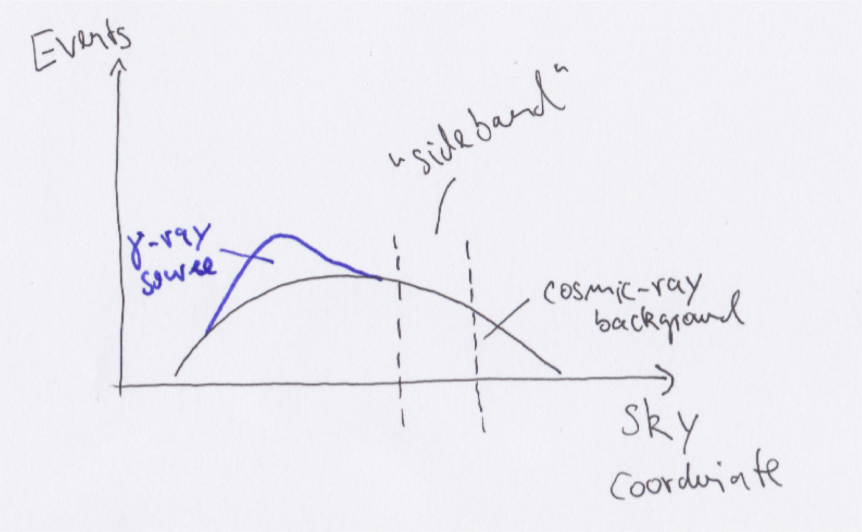
ISAPP school @ CERN, November 2018 A. Moralejo, gamma observations with IACTs 30

Background modelling for IACTs

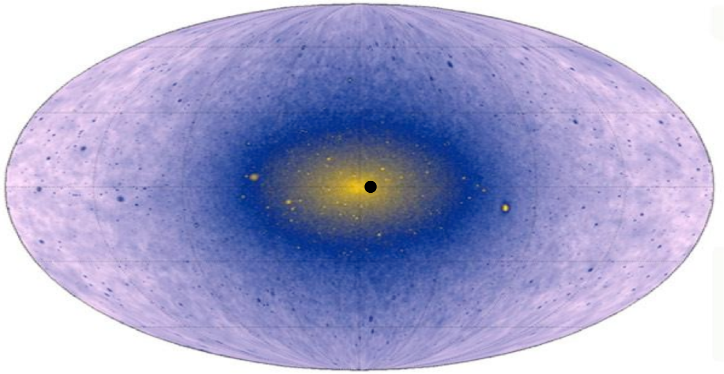


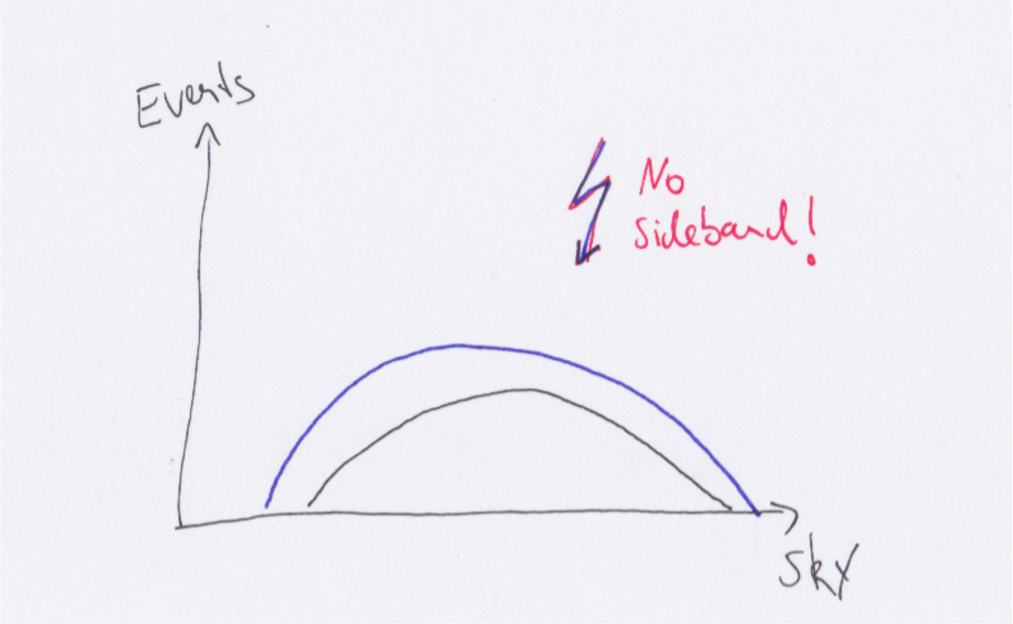






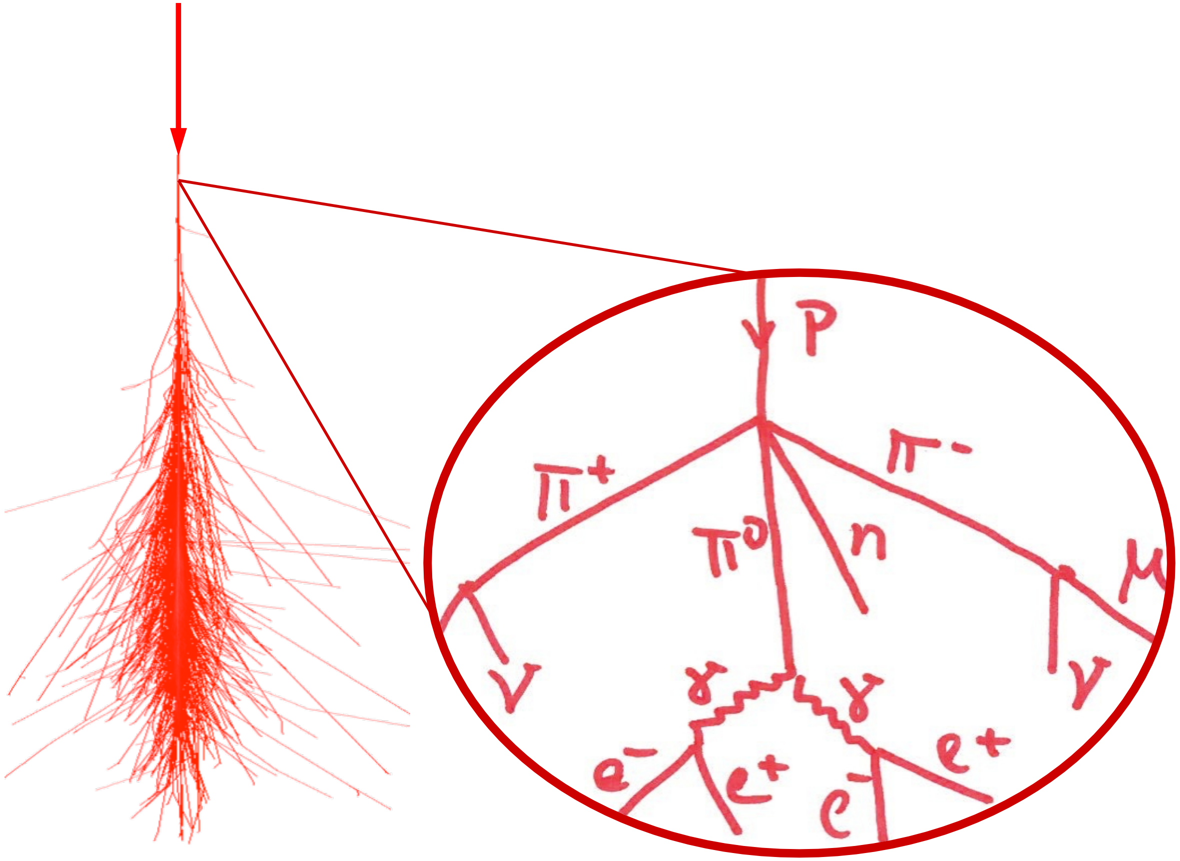
Background modelling for IACTs





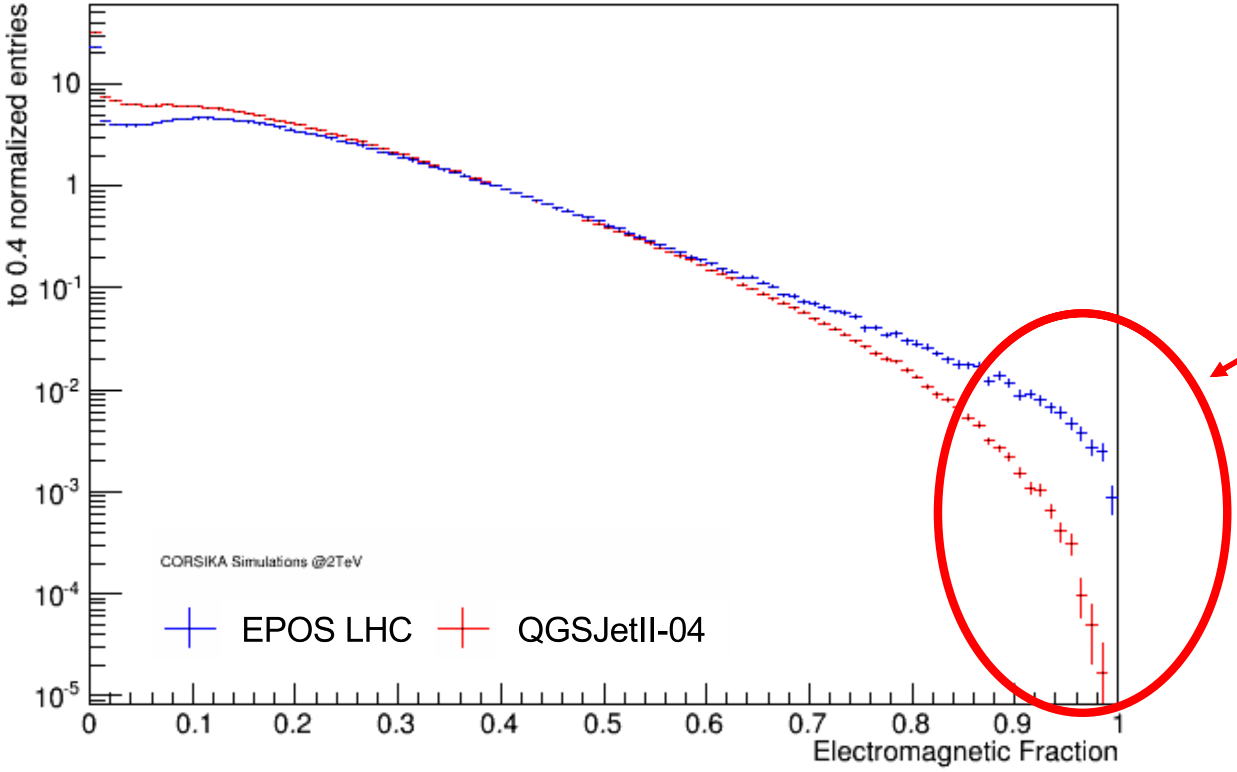
Solutions: invest precious observation time to measure empty fields or MC simulations!

Gamma-ray like proton showers

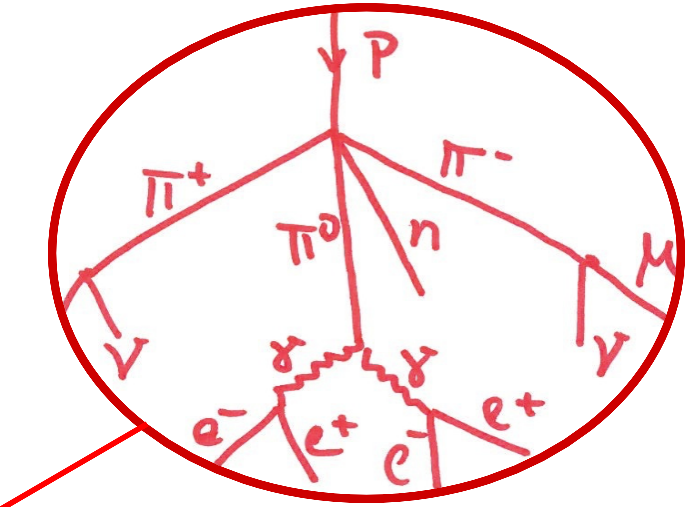


Gamma-ray like proton showers

CORSIKA simulation of 2 TeV protons



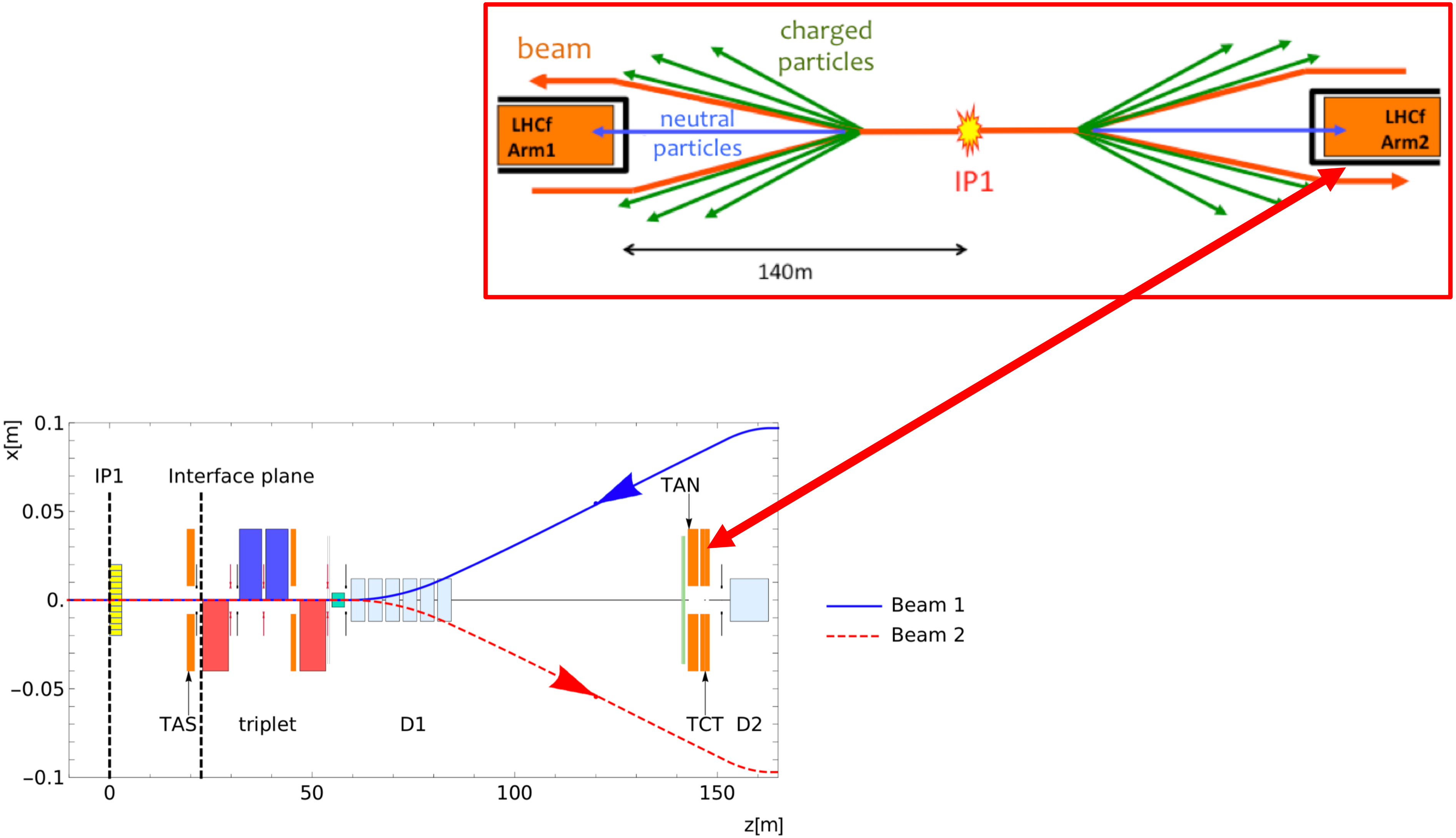
Christoph Maut



Showers for which nearly entire proton energy is converted into electromagnetic energy (electrons, photons, π^0‘s, eta‘s, etc).

ATLAS & LHCf to the rescue…?

See next talk!



Summary

Relevance for Astroparticle Physics

- Measurements of inelastic pp collisions essential for air shower physics
  - LHC precision in luminosity calibration exceptional for hadron collider
  - There are many unexplored areas, great terrain for eager astroparticle physicists to make a difference!

- Many many different dark matter searches are ongoing, so far no sign of new physics